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Circular Electron Positron Collider (**CEPC**)

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On behalf of CEPC Accelerator Group

Snowmass Agora on future colliders:
Circular e^+e^- colliders

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Contents

- **CEPC Physics Goals and Accelerator System**
 - Collider rings
 - Booster
 - Linac
 - MDI
 - SRF system and cryogenic system
- **CEPC Accelerator System Key Hardware R&D Progresses in TDR**
 - SRF (platform, cavities, other components, cryomodules...)
 - 650MHz high power and high efficiency klystrons
 - Magnets in collider and booster rings (dipoles, quadrupoles and sextupoles)
 - Linac injector hardwares
 - Final focus SC quadrupoles, sextupoles in IR region
- **CEPC Cost and Power Consumptions**
- **CEPC Time Plan and Perspective for Accelerator TDR and EDR Plans**
- **Backup slides for discussion and information**

CEPC-SppC Physics Goals in CDR (TDR)

- Circular Electron-Positron Collider (91, 160 , **240 GeV**, 360GeV)

- Higgs Factory (10^6 Higgs) :

- Precision study of Higgs(m_H , J^{PC} , couplings) , Similar & complementary to Linear Colliders
 - Looking for hints of new physics

- Z & W factory ($10^{10}\sim 10^{12} Z^0$) :

- precision test of SM
 - Rare decays ?

- Flavor factory: b, c, τ and QCD studies

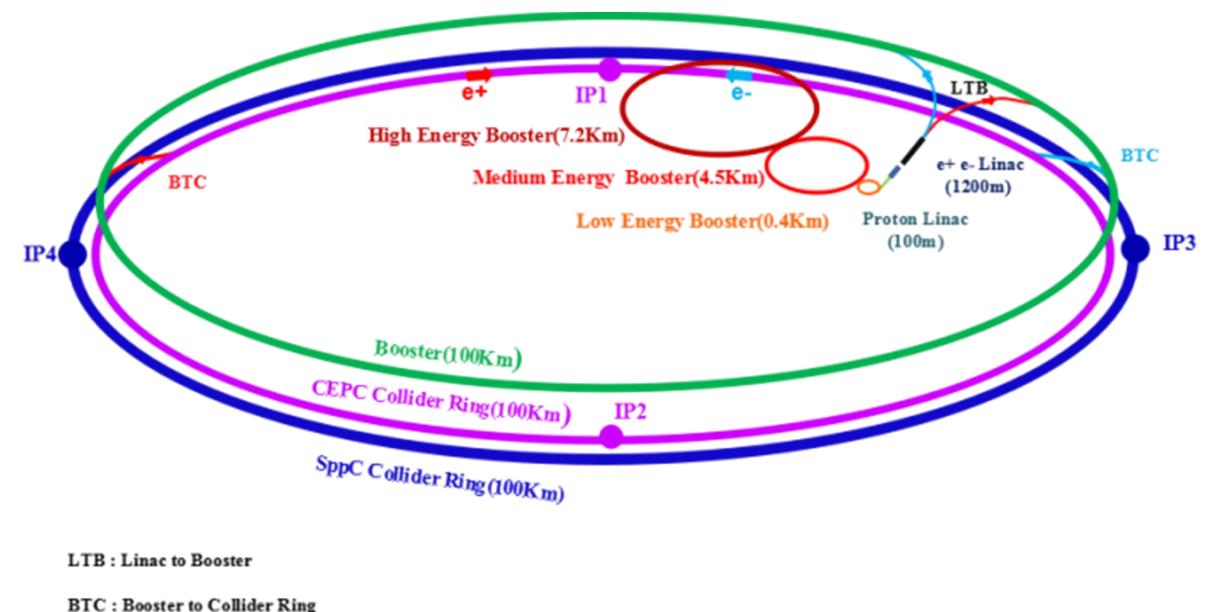
- Super proton-proton Collider(~100 TeV)

- Directly search for new physics beyond SM

- Precision test of SM

- e.g., h^3 & h^4 couplings

Baseline SR power/beam:
30MW, upgradable to 50MW



CEPC CDR Parameters

	<i>Higgs</i>	<i>W</i>	<i>Z (3T)</i>	<i>Z (2T)</i>
Number of IPs		2		
Beam energy (GeV)	120	80	45.5	
Circumference (km)		100		
Synchrotron radiation loss/turn (GeV)	1.73	0.34	0.036	
Crossing angle at IP (mrad)		16.5×2		
Piwinski angle	2.58	7.0	23.8	
Number of particles/bunch N_e (10^{10})	15.0	12.0	8.0	
Bunch number (bunch spacing)	242 (0.68μs)	1524 (0.21μs)	12000 (25ns+10%gap)	
Beam current (mA)	17.4	87.9	461.0	
Synchrotron radiation power /beam (MW)	30	30	16.5	
Bending radius (km)		10.7		
Momentum compact (10^{-5})		1.11		
β function at IP β_x^*/β_y^* (m)	0.36/0.0015	0.36/0.0015	0.2/0.0015	0.2/0.001
Emittance $\varepsilon_x/\varepsilon_y$ (nm)	1.21/0.0031	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP σ_x/σ_y (μm)	20.9/0.068	13.9/0.049	6.0/0.078	6.0/0.04
Beam-beam parameters ξ_x/ξ_y	0.031/0.109	0.013/0.106	0.0041/0.056	0.0041/0.072
RF voltage V_{RF} (GV)	2.17	0.47	0.10	
RF frequency f_{RF} (MHz) (harmonic)		650 (216816)		
Natural bunch length σ_z (mm)	2.72	2.98	2.42	
Bunch length σ_z (mm)	3.26	5.9	8.5	
HOM power/cavity (2 cell) (kw)	0.54	0.75	1.94	
Natural energy spread (%)	0.1	0.066	0.038	
Energy acceptance requirement (%)	1.35	0.4	0.23	
Energy acceptance by RF (%)	2.06	1.47	1.7	
Photon number due to beamstrahlung	0.1	0.05	0.023	
Lifetime _simulation (min)	100			
Lifetime (hour)	0.67	1.4	4.0	2.1
F (hour glass)	0.89	0.94	0.99	
Luminosity/IP L ($10^{34}\text{cm}^{-2}\text{s}^{-1}$)	2.93	10.1	16.6	32.1

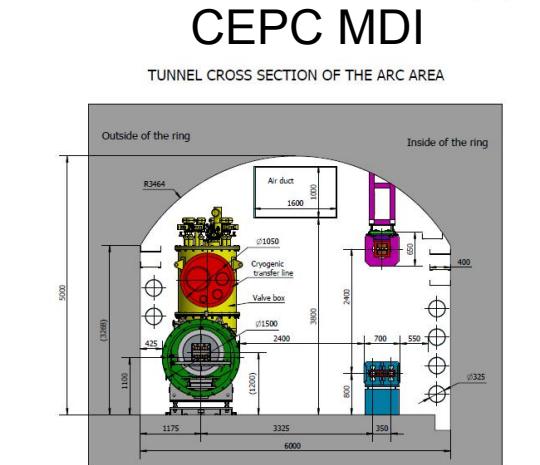
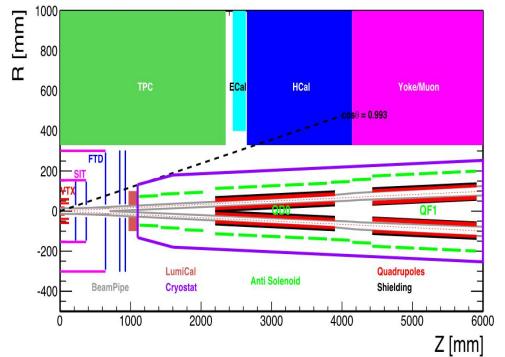
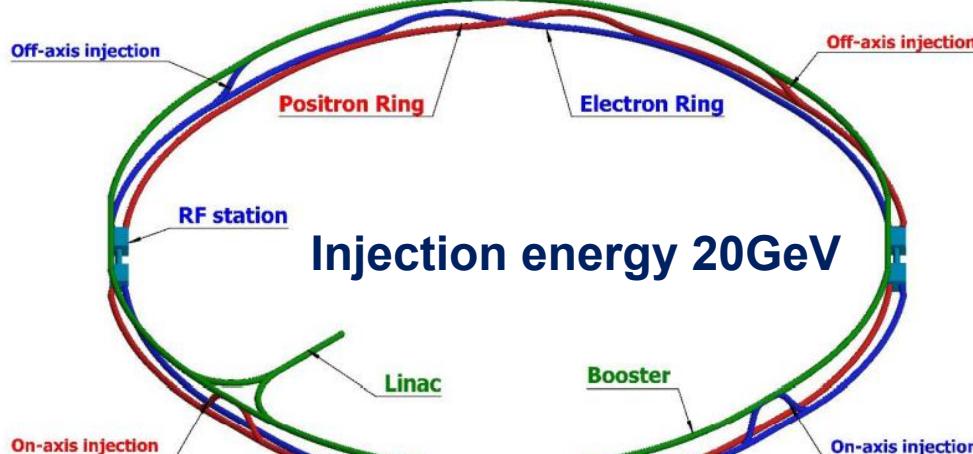
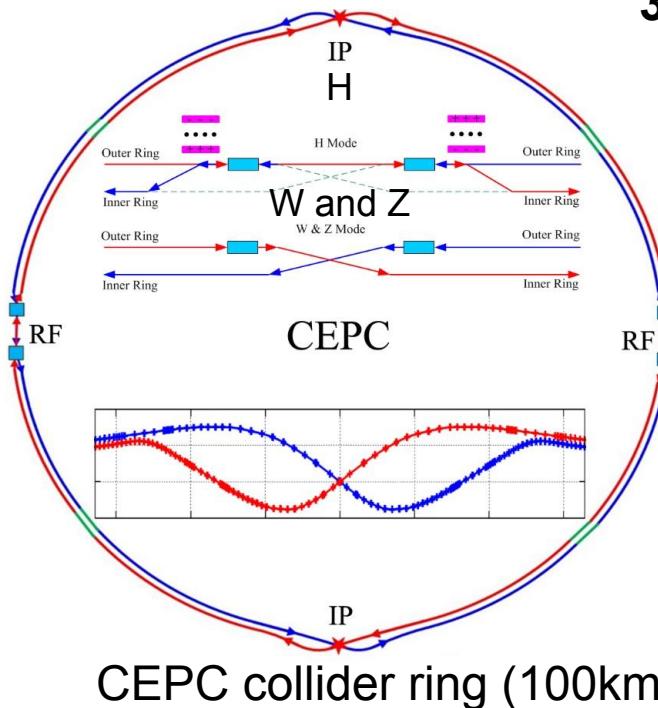
CEPC High Luminosity Parameters in TDR

	ttbar	Higgs	W	Z
Number of IPs		2		
Circumference [km]		100.0		
SR power per beam [MW]		30		
Half crossing angle at IP [mrad]		16.5		
Bending radius [km]		10.7		
Energy [GeV]	180	120	80	45.5
Energy loss per turn [GeV]	9.1	1.8	0.357	0.037
Piwinski angle	1.21	5.94	6.08	24.68
Bunch number	35	249	1297	11951
Bunch spacing [ns]	4524	636	257	25 (10% gap)
Bunch population [10^{10}]	20	14	13.5	14
Beam current [mA]	3.3	16.7	84.1	803.5
Momentum compaction [10^{-5}]	0.71	0.71	1.43	1.43
Beta functions at IP (b_x/b_y) [m/mm]	1.04/2.7	0.33/1	0.21/1	0.13/0.9
Emittance (ex/ey) [nm/pm]	1.4/4.7	0.64/1.3	0.87/1.7	0.27/1.4
Beam size at IP (σ_{x}/σ_{y}) [μm/nm]	39/113	15/36	13/42	6/35
Bunch length (SR/total) [mm]	2.2/2.9	2.3/3.9	2.5/4.9	2.5/8.7
Energy spread (SR/total) [%]	0.15/0.20	0.10/0.17	0.07/0.14	0.04/0.13
Energy acceptance (DA/RF) [%]	2.3/2.6	1.7/2.2	1.2/2.5	1.3/1.7
Beam-beam parameters (ksix/ksiy)	0.071/0.1	0.015/0.11	0.012/0.113	0.004/0.127
RF voltage [GV]	10	2.2	0.7	0.12
RF frequency [MHz]	650	650	650	650
HOM power per cavity (5/2/1cell)[kw]	0.4/0.2/0.1	1/0.4/0.2	-1.8/0.9	-/-5.8
Longitudinal tune Qs	0.078	0.049	0.062	0.035
Beam lifetime (bhabha/beamstrahlung)[min]	81/23	39/40	60/700	80/18000
Beam lifetime [min]	18	20	55	80
Hour glass Factor	0.89	0.9	0.9	0.97
Luminosity per IP[$1e34/cm^2/s$]	0.5	5.0	16	115

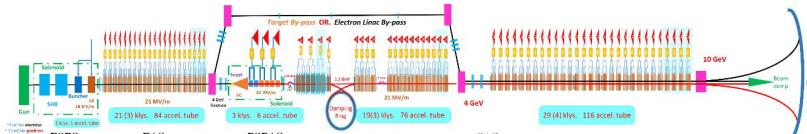
CEPC TDR Layout

CEPC as a Higgs Factory : ttbar, H, W, Z, followed by a SppC ~100TeV

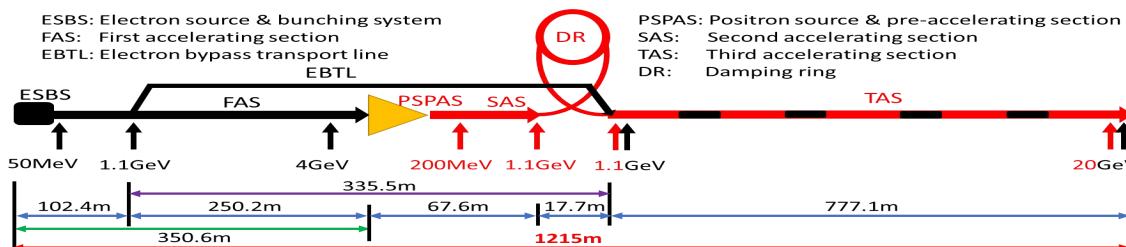
30MW SR power per beam (upgradale to 50MW)



CEPC CDR S-band 10GeV injector

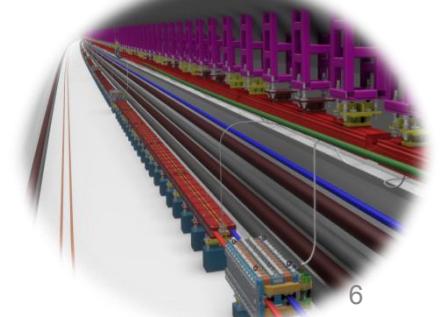


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Snowmass Agora 2: Circular e+e- Colliders

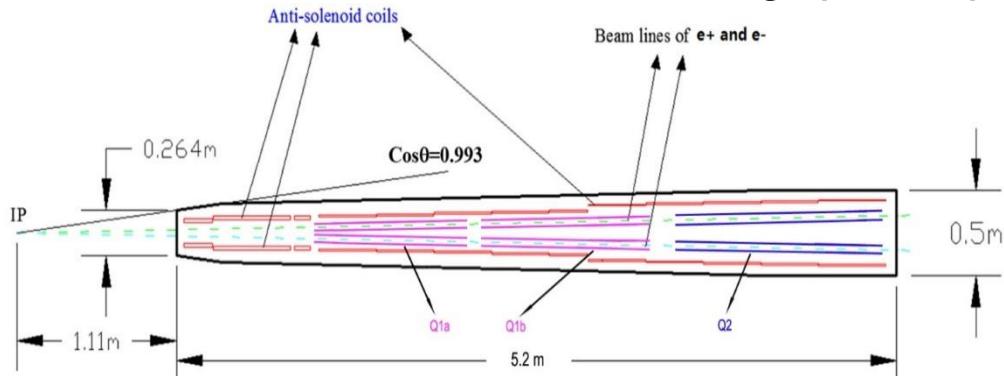
CEPC Linac injector of 20GeV



CEPC Collider Ring IR for all Energies

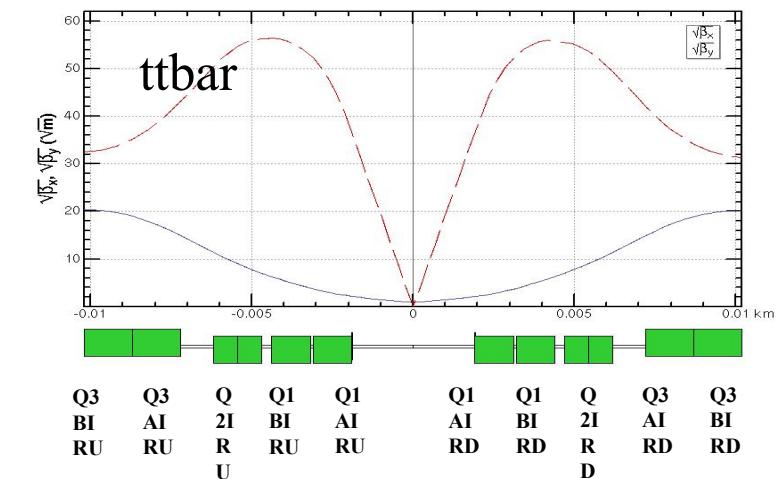
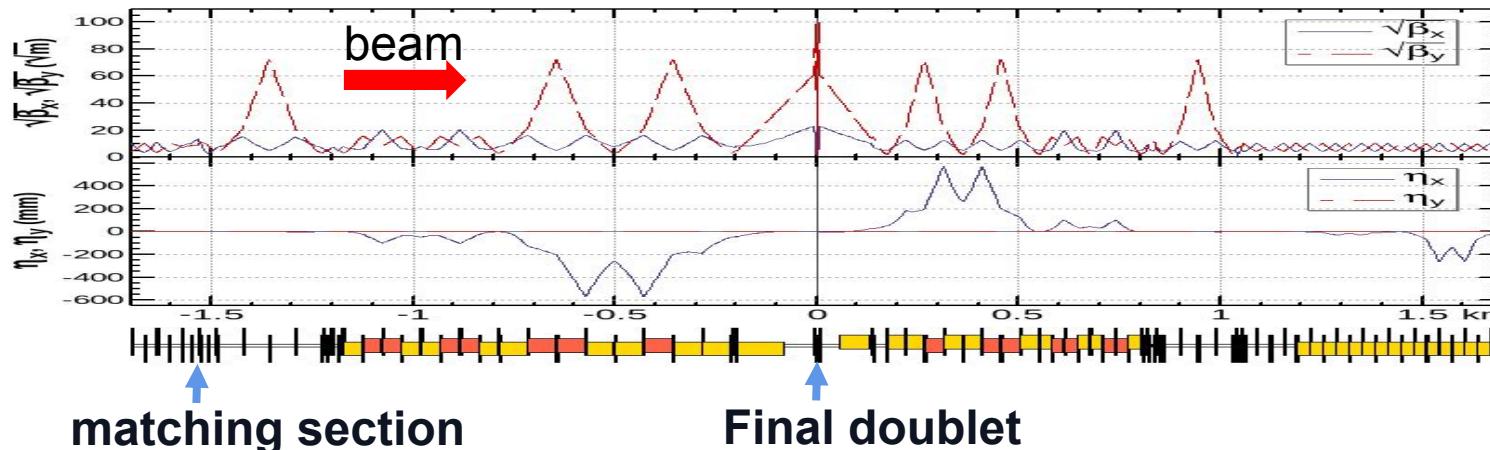
($t\bar{t}$ -bar, **Higgs**, W and Z)

For the interaction region, the IP beta functions are refitted with the different combination of final doulets and the matching quadruples.



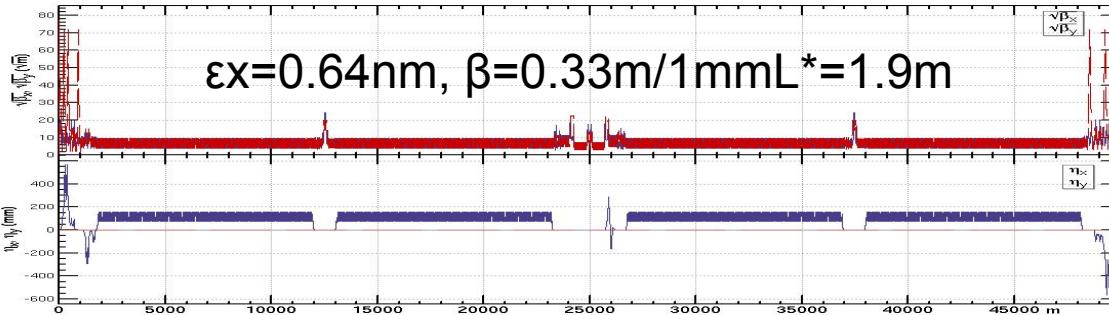
	QD	QF
Z	Q1A	Q1B
W/H	Q1A+Q1B	Q2
$t\bar{t}$ bar	Q1A+Q1B+Q2	add quad Q3A and Q3B

Higgs: $L^*=1.9\text{m}$, $LQ1A=1.22\text{m}$, $LQ1B=1.22\text{m}$, $LQ2=1.5\text{m}$, $d=0.3\text{m}$, $GQ1A=142\text{T/m}$, $GQ1B=96\text{T/m}$, $GQ2=56\text{T/m}$



CEPC Collider Ring TDR Lattice Dynamic Aperture with Errors for Higgs

Beam physics challenging point



Component	Δx (mm)	Δy (mm)	$\Delta \theta_z$ (mrad)	Field error
Dipole	0.10	0.10	0.1	0.01%
Arc Quadrupole	0.10	0.10	0.1	0.02%
IR Quadrupole	0.05	0.05	0.05	
Sextupole	0.10	0.10	0.1	

Effects included in tracking

Synchrotron motion

Radiation loss in all magnets

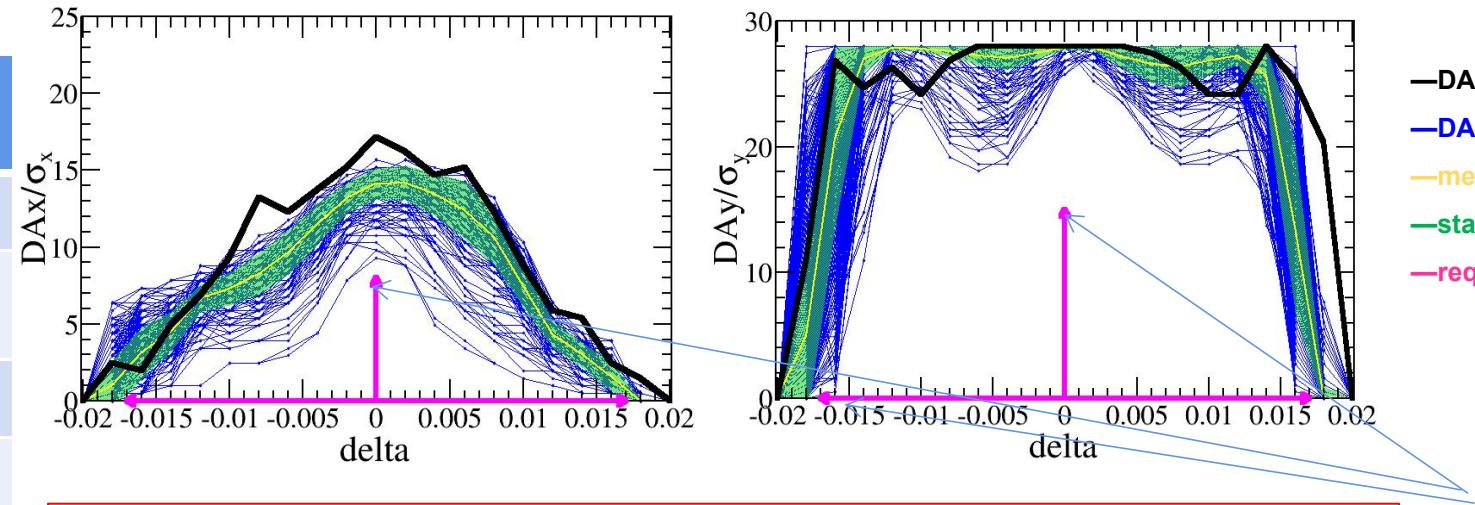
Tapering

Crab waist sextupole

Maxwellian fringes

Kinematic terms

Finite length of sextupole



Lattice version cepc.lat.diff.8713.346.2p used
The DA with errors of TDR lattice satisfy the design goal

Component	Δx (mm)	Δy (mm)	$\Delta \theta_z$ (mrad)	Field error
IR Quadrupole	0.1	0.1	0.01	

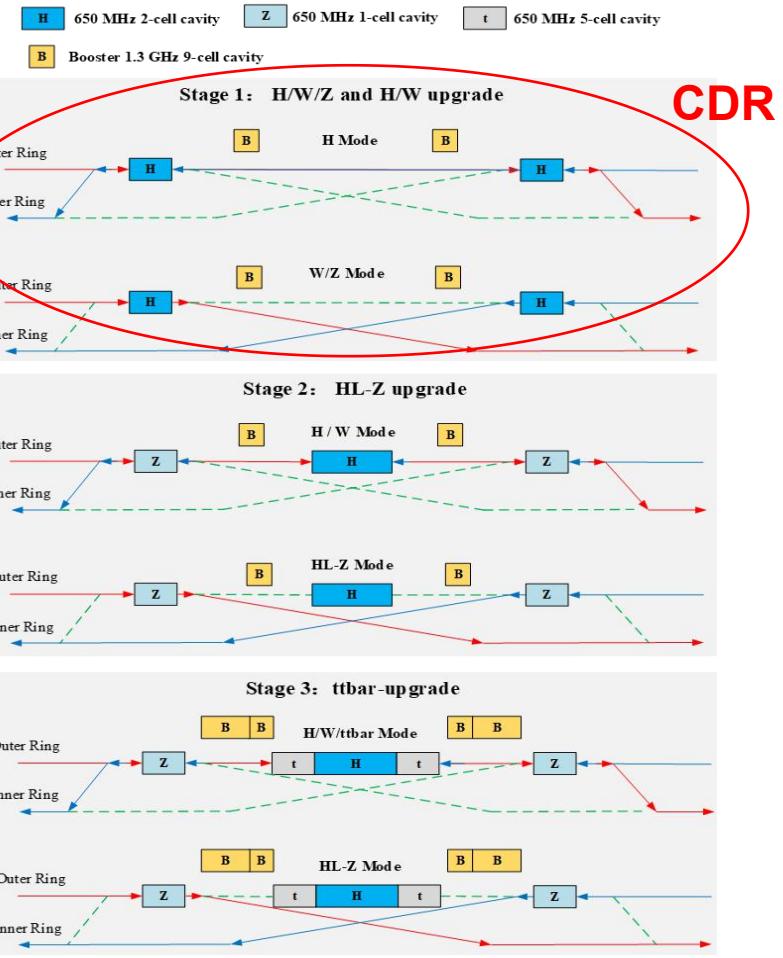
DA design goal
 $8\sigma_x \times 15\sigma_y$ & 0.017

IR Quadrupole error of 0.1mm error 50% of 167 seeds succeeded

CEPC TDR RF Parameters (Collider Ring)

Version. 2022.01.12. Machine parameters: 2021.11
 30 MW SR power per beam for each mode.
 ttbar and Higgs half fill with common cavities for two rings, W and Z with separate cavities for two rings, Z use high current 1-cell cavity with RF bypass

	ttbar		Higgs	W	Z
	Additional 5-cell cavities	Existing 2-cell cavities			
Luminosity / IP [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]		0.5	5	16	115
RF voltage [GV]		10 (7.8 + 2.2)	2.2	0.7	0.12
Beam current / beam [mA]		3.4	16.4	84	803
Bunch charge [nC]		32	22	21.6	22.4
Bunch length [mm]		2.9	3.9	4.9	8.7
650 MHz cavity number	240	240	240	120/ring	30/ring
Cell number / cavity	5	2	2	2	1
Gradient [MV/m]	28.5	20	20	12.7	8.7
Q_0 @ 2 K at operating gradient (long term)	5E10		2E10		
HOM power / cavity [kW]	0.4	0.16	0.45	0.93	2.9
Input power / cavity [kW]	194	56	250	250	1000
Optimal Q_L	1E7	7E6	1.6E6	6.4E5	7.5E4
Optimal detuning [kHz]	0.01	0.02	0.1	0.9	13.3
Cavity number / klystron	4	12	2	2	1
Klystron power [kW]	1400	1400	800	800	1400
Klystron number	60	20	120	60	60
Cavity number / cryomodule	4		6		1
Cryomodule number	60		40		30
Total cavity wall loss @ 2 K [kW]	9.5		4.7	1.9	0.45



- RF staging and bypass. Seamless mode switching.
- Z lumi in Stage 1: 1/6 Lumi if CAV HOM < 1 kW.
- If start from Stage 2. W: 1/2 Lumi. Z: 1/12 Lumi.
- Transfer Higgs/ttbar RF power to high lumi Z.
- Klystron power and HOM handling capacity allow for 50 MW upgrade of ttbar, H, W. Add 30 cavities for Z 50 MW upgrade.

CEPC Booster TDR parameters

- Injection energy: $10\text{GeV} \rightarrow 20\text{GeV}$
- Max energy: $120\text{GeV} \rightarrow 180\text{GeV}$
- Lower emittance — new lattice

		$\#$	H	W	Z
Beam energy	GeV		20		
Bunch number	Injection	37	240	1230	3840 5760
Threshold of single bunch current	μA	7.18	4.58		3.8
Threshold of beam current (limited by coupled bunch instability)	mA		27		
Bunch charge	nC	1.07	0.78	0.81	0.89 0.92
Single bunch current	μA	3.2	2.3	2.4	2.7 2.78
Beam current	mA	0.12	0.56	2.99	10.3 16.0
Energy spread	%		0.016		
Synchrotron radiation loss/turn	MeV		1.3		
Momentum compaction factor	10^{-5}		1.12		
Emittance	nm		0.035		
Natural chromaticity	H/V		-372/-269		
RF voltage	MV	438.0	197.1		122.4
Betatron tune ν_x/ν_y			321.23/117.18		
Longitudinal tune		0.13	0.087		0.069
RF energy acceptance	%	5.4	3.6		2.8
Damping time	s		10.4		
Bunch length of linac beam	mm		0.5		
Energy spread of linac beam	%		0.16		
Emittance of linac beam	nm		10		

*Diameter of beam pipe is 55mm for instability estimation.

Extraction		$\#$	H		W	Z	
		Off axis injection	Off axis injection	On axis injection	Off axis injection	Off axis injection	Off axis injection
Beam energy	GeV	180		120	80		45.5
Bunch number		37	240	233+7	1230	3840	5760
Maximum bunch charge	nC	0.96	0.7	23.2	0.73	0.8	0.83
Maximum single bunch current	μA	2.9	2.1	69.7	2.2	2.4	2.5
Threshold of single bunch current	μA	95		79			
Threshold of beam current (limited by RF system)	mA	0.3		1	4	10	16
Beam current	mA	0.11	0.51	0.99	2.69	9.2	14.4
Bunches per pulse of Linac		1		1	1		2
Time for ramping up	s	7.3		4.5	2.7		1.6
Injection duration for top-up (Both beams)	s	30.0	23.3	32.8	39.3	134.7	128.2
Injection interval for top-up	s	65		38	155		153.5
Current decay during injection interval					3%		
Energy spread	%	0.15		0.099	0.066		0.037
Synchrotron radiation loss/turn	GeV	8.45		1.69	0.33		0.034
Momentum compaction factor	10^{-5}				1.12		
Emittance	nm	2.83		1.26	0.56		0.19
Natural chromaticity	H/V				-372/-269		
Betatron tune ν_x/ν_y					321.27/117.19		
RF voltage	GV	9.3		2.05	0.59		0.284
Longitudinal tune		0.13		0.087	0.069		0.069
RF energy acceptance	%	1.34		1.31	1.6		2.6
Damping time	ms	14.2		47.6	160.8		879
Natural bunch length	mm	2.0		2.0	1.7		0.96
Full injection from empty ring	h	0.1	0.14	0.16	0.27	1.8	0.8

CEPC TDR RF Parameters (Booster Ring)

Version. 2022.01.12. Machine parameters: 2021.11 30 MW Collider SR power per beam for each mode. 20 GeV injection.	ttbar	Higgs off/on-axis	W	Z high current
Extraction beam energy [GeV]	180	120	80	45.5
Extraction average SR power [MW]	0.087	0.09	0.01	0.004
Bunch charge [nC]	0.96	0.7	0.73	0.83
Beam current [mA]	0.11	0.5/1	2.7	14.3
Injection RF voltage [GV]	0.438	0.197	0.122	0.122
Extraction RF voltage [GV]	9.3	2.05	0.59	0.28
Extraction bunch length [mm]	1.9	1.9	1.6	0.9
Cavity number (1.3 GHz 9-cell)	336	96	64	16
Extraction gradient [MV/m]	26.7	20.6	8.9	17.1
Q ₀ @ 2 K at operating gradient (long term)	1E10			
Q _L	4E7	1E7		
Cavity bandwidth [Hz]	33	130		
Peak HOM power per cavity [W]	0.4	1.2/2.3	7.8	105
Input peak power per cavity [kW]	7.5	16/21.4	15	31
SSA peak power [kW] (one cavity per SSA)	10	25	25	40
Cryomodule number (8 cavities per module)	42	12	8	2

CDR Higgs energy:

- collider ring: 240 2cell 650MHz cavities
- booster: 96 1.3GHz 9cell cavities
- Nb consumption: 20 tons**

For ttbar energy:

In addition to CDR Higgs energy, SRF cavity numbers have to be increased:

- collider ring:+350 5cell 650MHz cavities
- booster ring:+350 1.3GHz 9 cell cavities
- Additional Nb consumption:65 tons**

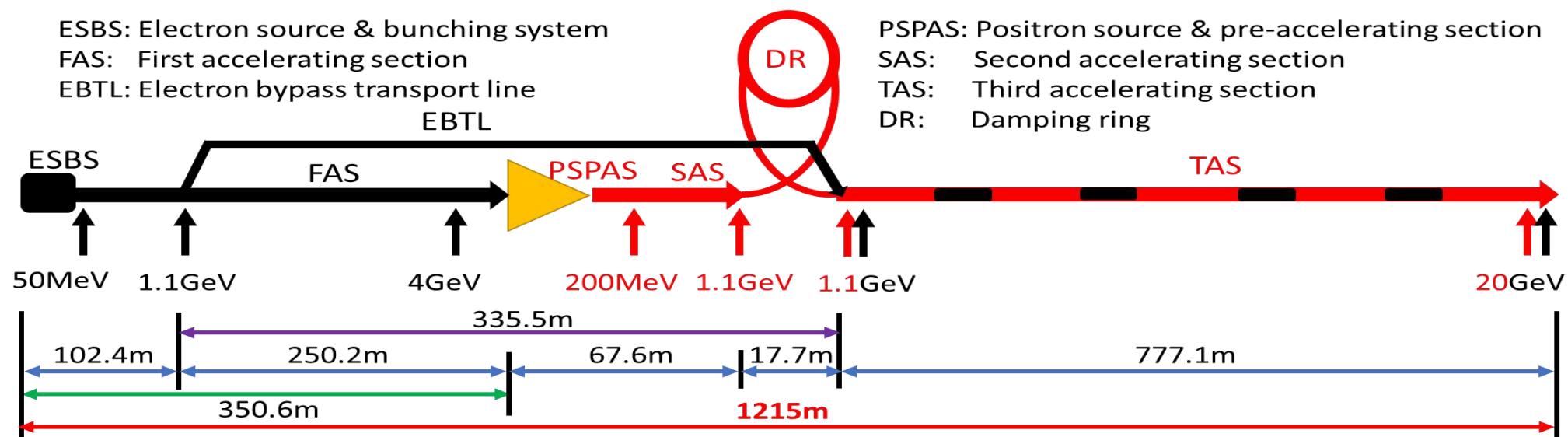
For 30MW SR/beam Mode at Higgs energy,
the cryogenic system need **32000liter**
Helium

For 50MW/beam SR Mode:

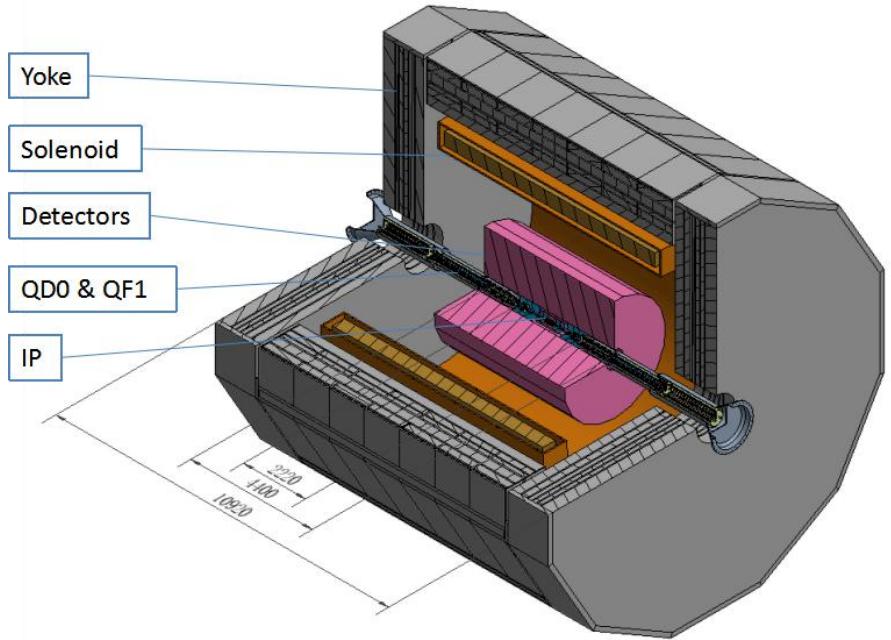
at Higgs energy, the cryogenic system
needs 42000liter Helium; at ttbar energy
130000liter Helium needed

CEPC 20GeV Linac for TDR

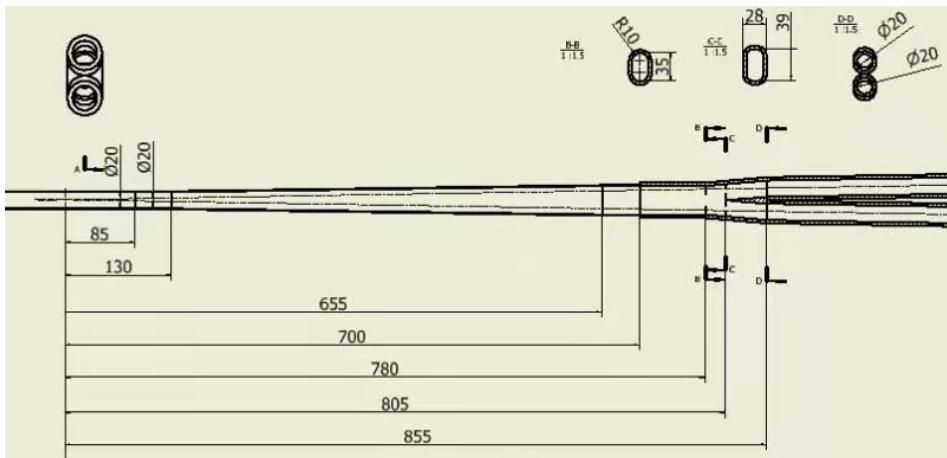
- EBTL is in vertical plane with 1.2 m separation
 - Avoid interference with energy analyzing station, transport lines between the Linac and damping ring, waveguide and positron source
 - Reduce the tunnel width
- Accelerating structure
 - S-band: FAS/PSPAS/SAS
 - C-band: TAS



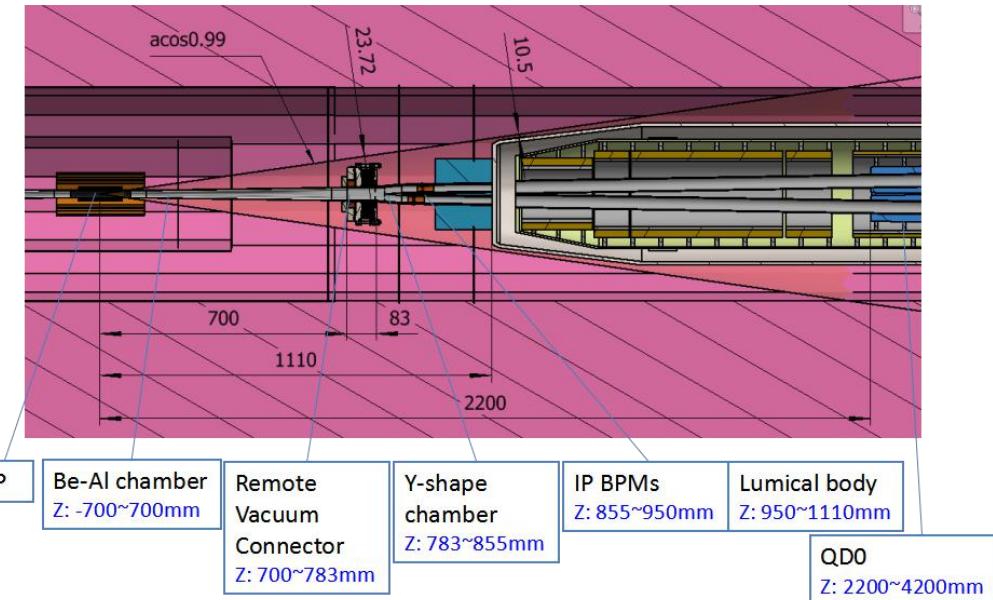
CEPC MDI Study Progresses



- IR Superconducting magnet design
- IR beam pipe
- Synchrotron radiation
- Beam loss background
- Shielding
- Mechanical support
- Full detector simulation



- Central beryllium pipe inner diameter changes from 28mm(CDR) to 20mm
- There is no SR photons hitting the central beam pipe in normal conditions.
- Single layer beam pipe with water cooling, SR heat load is not a problem.



■ All the devices are **within** the detective angle, $\text{acos}0.99$.

$$L^*=1.9\text{m}, \theta_c=33\text{mrad}, \beta_x^*=0.33\text{m}, \beta_y^*=1.0\text{mm}, \text{Emittance}=0.68\text{nm}$$

- Strength requirements of anti-solenoids (peak field $B_z \sim 7.2\text{T}$)
- Two-in-one type SC quadrupole coils (Peak field 3.8T & 141T/m) with room temperature vacuum chamber & Iron yoke

CEPC CDR Power for Higgs and Z

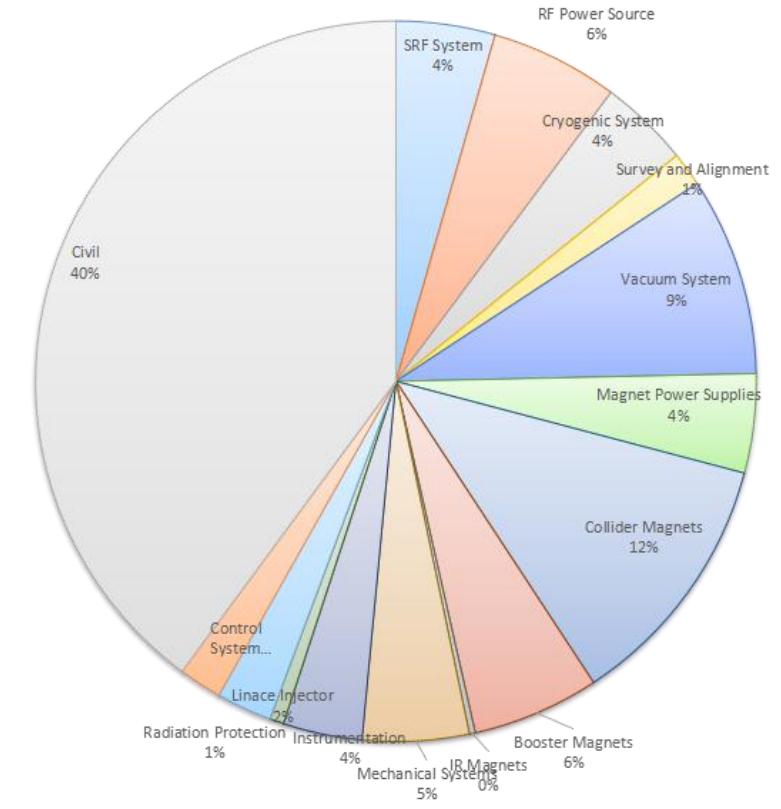
	System for Higgs (30MW)	Location and electrical demand(MW)						Total (MW)
		Ring	Booster	LINAC	BTL	IR	Surface building	
1	RF Power Source	103.8	0.15	5.8				109.75
2	Cryogenic System	11.62	0.68			1.72		14.02
3	Vacuum System	9.784	3.792	0.646				14.222
4	Magnet Power Supplies	47.21	11.62	1.75	1.06	0.26		61.9
5	Instrumentation	0.9	0.6	0.2				1.7
6	Radiation Protection	0.25		0.1				0.35
7	Control System	1	0.6	0.2	0.005	0.005		1.81
8	Experimental devices					4		4
9	Utilities	31.79	3.53	1.38	0.63	1.2		38.53
10	General services	7.2		0.2	0.15	0.2	12	19.75
	Total	213.554	20.972	10.276	1.845	7.385	12	266.032

266MW

	System for Z	Location and electrical demand(MW)						Total (MW)
		Ring	Booster	LINAC	BTL	IR	Surface building	
1	RF Power Source	57.1	0.15	5.8				63.05
2	Cryogenic System	2.91	0.31			1.72		4.94
3	Vacuum System	9.784	3.792	0.646				14.222
4	Magnet Power Supplies	9.52	2.14	1.75	0.19	0.05		13.65
5	Instrumentation	0.9	0.6	0.2				1.7
6	Radiation Protection	0.25		0.1				0.35
7	Control System	1	0.6	0.2	0.005	0.005		1.81
8	Experimental devices					4		4
9	Utilities	19.95	2.22	1.38	0.55	1.2		25.3
10	General services	7.2		0.2	0.15	0.2	12	19.75
	Total	108.614	9.812	10.276	0.895	7.175	12	148.772

149MW

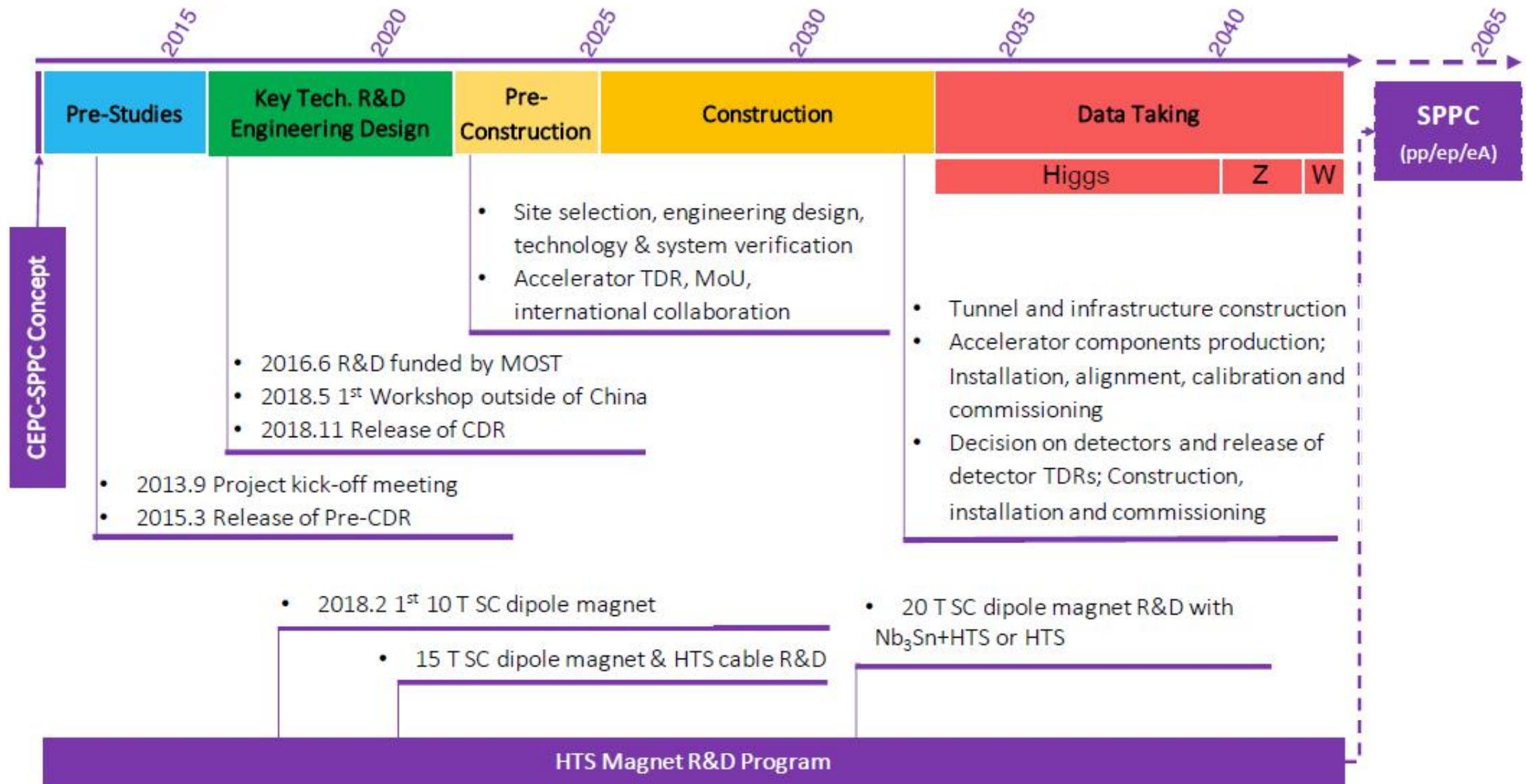
CEPC CDR Cost Breakdown (no detector)



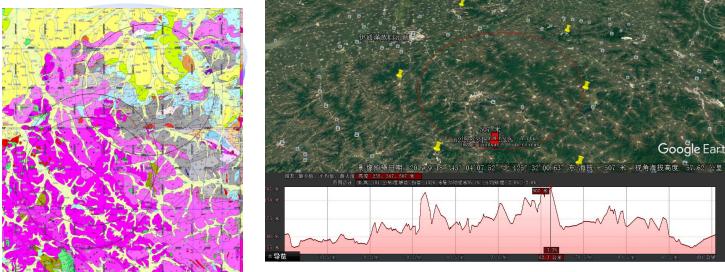
The total cost of CEPC~35Billion RMB~5Billion US\$
(Accelerator+2 Detectors+Civil+Contingence)

In addition to machine operation power auxiliary cooling power of about 15~30MW depending on the site annual average temperature

CEPC Project Timeline

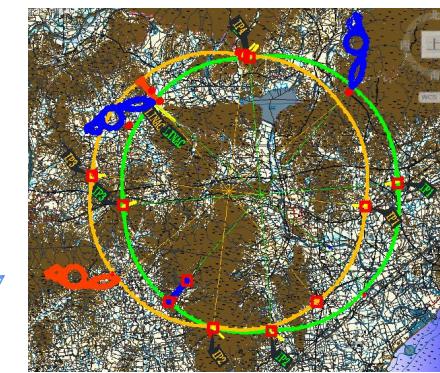


CEPC Siting Status

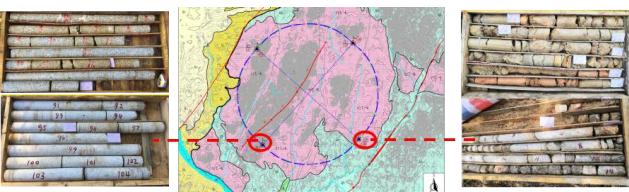


2019. 12月8-11 and 2020. 1. 8-10
Chuangchun sitings update

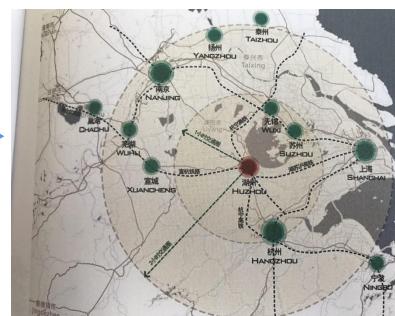
5 Three companies are working
on siting and issues



2020.9.14-18 Qinhuangdao updated



In 2021, Changsha site
has some progress
with local government
starting a review process



2019. 12. 16-17 Huzhou siting update



2019. 08. 19-20 Changsha
siting update

- 1) Qinhuangdao, Hebei Province (Completed in 2014)
- 2) Huangling, Shanxi Province (Completed in 2017)
- 3) Shenshan, Guangdong Province (Completed in 2016)
- 4) Huzhou, Zhejiang Province (Started in March 2018)
- 5) Chuangchun, Jilin Province (Started in May 2018)
- 6) Changsha, Hunan Province (Started in Dec. 2018)

CEPC Accelerator TDR R&D Priority, Plan and Test Facilities

(Detailed information please look at backup slides)

- 1) CEPC 650MHz 800kW high efficiency klystron (80%) (at the end of 2021 complete the fabrication, finish test in 2022)
- 2) High precision booster dipole magnet (critical for booster operation)
(Complete real size magnet model in 2022)
- 3) CEPC 650MHz SC accelerator system, including SC cavities and cryomules (Complete test cryomodule in 2022)
- 4) Collider dual aperture dipole magnets, dual aperture quadrupoles and sextupole magnets(Complete real size model in 2022)
- 5) Vacuum chamber system (Complete fabrication and costing test in 2022)
- 6) SC quadrupole magnets including cryostate (Complete short test model in 2022, dual aperture SC quadrupole in 2025)

- 7) MDI mechanic system (Remote vacuum connection be started in 2022)
- 8) Collimator (be started in 2022)
- 9) Linac components (Complete key components test in 2022, C-band linac be started in 2022)
- 10) Civil preliminary engineering design (Reference implementation design complete in 2022)
- 11) Plasma injector (Alternative injector technology, start electron acceleration test in 2022)
- 12) 18KW@4.5K cryoplant (Company) (Complete in 2025)

...

SppC technology R&D

Ion based superconducting materials and high field magnets

Perspective for Accelerator TDR and EDR Plans

- **CEPC Accelerator TDR completion time: Dec. 2022**

- Consistent TDR high luminosity parameter design as Higgs factory
- Key components with prototyping, technical feasibility demonstrated, no technical show stopper
- Design and R&D technical documentation (Data, drawings, etc.)
- CEPC accelerator TDR document release in 2023

- **CEPC Accelerator EDR Phase Plan:Jan. 2023-Dec. 2025**

- CEPC site study converging to one or two with detailed feasibility studies (tunnel and infrastructures, environment)
- Engineering design of CEPC accelerator systems and components towards fabrication in an industrial way
- Site dependent civil engineering design implementation preparation
- EDR document completed for government's approval of starting construction in 2026 (the starting of the "15th five year plan")
- ... (CEPC accelerator EDR phase plan needs more discussions)

Acknowledgements

- Thanks go to CEPC-SppC accelerator team's hardworks, international and CIPC collaborations
- Special thanks to CEPC SC, IAC and IARC's critical comments, suggestions and encouragement

Backup slides:

CEPC Accelerator System Key Hardware R&D Progresses in TDR

Agora: ITF Comparison Categories

	CEPC
CoM Energy and expandability, GeV	360,240,160,91
Peak Luminosity ($10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)	0.5,5,16,115@30MW SR power/beam
IP difficulties, beamstrahlung	beta_y=1mm,
Length of facility, km	302
Length of new accelerators, km	302
Beam parameters challenges (e+, alignment, etc.)	SC Quadupole 10um, other magnets 100um
Special technologies	SRF, High efficiency klystrons, long magnets
R&D/validation (yrs. needed); constr. start year	4y TDR+3y EDR
Construction time, yrs.	8
Cost (wrt ILC) (+/-, %), level of maturity	CDR Cost for Higgs factory: 5Billion USD
Environment issues: AC power consumption of facility, resources (Nb, LHe...) needed	300MW, 85Ton Nb for ttbar, 20Ton Nb for Higgs. For 30MW/beam SR power at Higgs energy, cryogenic system needs 32000liter Helium, for 50MW for ttbar, 130000liters needed

CEPC CDR-Higgs

Peak Luminosity = $3 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$

Ingetrated Luminosity = 5.6 ab^{-1}

Higgs annual luminosity = 0.8 ab^{-1}

CEPC CDR Vol. I, Accelerator

IHEP-CEPC-DR-2018-01
IHEP-AC-2018-01

CEPC
Conceptual Design Report

Volume I - Accelerator

The CEPC Study Group
August 2018

CEPC TDR-Higgs

Peak Luminosity = $5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$

Ingetrated Luminosity = 9.3 ab^{-1}

Higgs annual luminosity = 1.3 ab^{-1}

CEPC Higss Physics White Paper

Chinese Physics C Vol. 43, No. 4 (2019) 043002

Precision Higgs physics at the CEPC*

Fenfen An(安芬芬)^{4,23} Yu Bai(白羽)⁹ Chunhui Chen(陈春晖)²³ Xin Chen(陈新)⁵ Zhenxing Chen(陈振兴)³
Joao Guimaraes da Costa⁴ Zhenwei Cui(崔振威)³ Yaquan Fang(方亚泉)^{4,6,34;1)} Chengdong Fu(付成栋)⁴
Jun Gao(高俊)¹⁰ Yanyan Gao(高艳彦)²² Yuanning Gao(高原宁)³ Shaofeng Ge(葛韶峰)^{15,29}
Jiayin Gu(顾嘉荫)^{13,2)} Fangyi Guo(郭方毅)^{1,4} Jun Guo(郭军)¹⁰ Tao Han(韩涛)^{5,31} Shuang Han(韩爽)⁴
Hongjian He(何红建)^{11,10} Xianke He(何显柯)¹⁰ Xiaogang He(何小刚)^{11,10,20} Jifeng Hu(胡继峰)¹⁰
Shih-Chieh Hsu(徐士杰)³² Shan Jin(金山)⁸ Maoqiang Jing(荆茂强)^{4,7} Susmita Jyotishmati³³ Ryuta Kiuchi⁴
Chia-Ming Kuo(郭家铭)²¹ Peizhu Lai(赖培筑)²¹ Boyang Li(李博扬)⁵ Congqiao Li(李聪乔)³ Gang Li(李刚)^{4,34;3)}
Haifeng Li(李海峰)¹² Liang Li(李亮)¹⁰ Shu Li(李数)^{11,10} Tong Li(李通)¹² Qiang Li(李强)³ Hao Liang(梁浩)^{4,6}
Zhijun Liang(梁志均)⁴ Libo Liao(廖立波)⁴ Bo Liu(刘波)^{4,23} Jianbei Liu(刘建北)¹ Tao Liu(刘涛)¹⁴
Zhen Liu(刘真)^{26,30;4)} Xinchou Lou(娄辛丑)^{4,6,33,34} Lianliang Ma(马连良)¹² Bruce Mellado^{17,18} Xin Mo(莫欣)⁴
Mila Pandurovic¹⁶ Jianming Qian(钱剑明)^{24,5)} Zhuoni Qian(钱卓妮)¹⁹ Nikolaos Rompotis²²
Manqi Ruan(阮曼奇)^{4,6)} Alex Schuy³² Lianyou Shan(单连友)⁴ Jingyuan Shi(史静远)⁹ Xin Shi(史欣)⁴
Shufang Su(苏淑芳)²⁵ Dayong Wang(王大勇)³ Jin Wang(王锦)⁴ Liantao Wang(王连涛)^{27,7)}
Yifang Wang(王贻芳)^{4,6} Yuqian Wei(魏彧骞)⁴ Yue Xu(许悦)⁵ Haijun Yang(杨海军)^{10,11} Ying Yang(杨迎)⁴
Weiming Yao(姚为民)²⁸ Dan Yu(于丹)⁴ Kaili Zhang(张凯栗)^{4,6,8)} Zhaoru Zhang(张照茹)⁴
Mingmu Zhao(赵明锐)² Xianghu Zhao(赵祥虎)⁴ Ning Zhou(周宁)¹⁰

CEPC CDR Vol. II, Physics/Detector

IHEP-CEPC-DR-2018-02.
IHEP-EP-2018-01
IHEP-TH-2018-01

CEPC
Conceptual Design Report

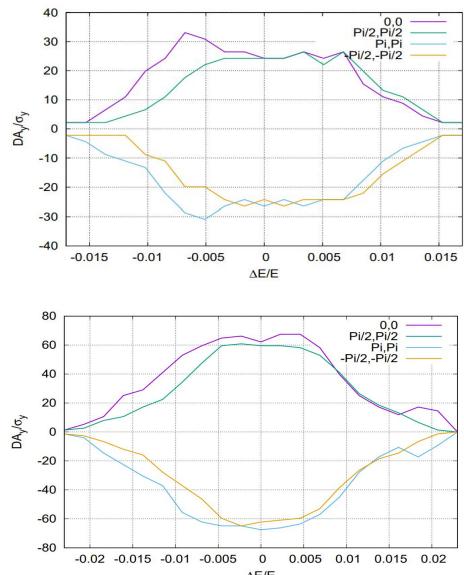
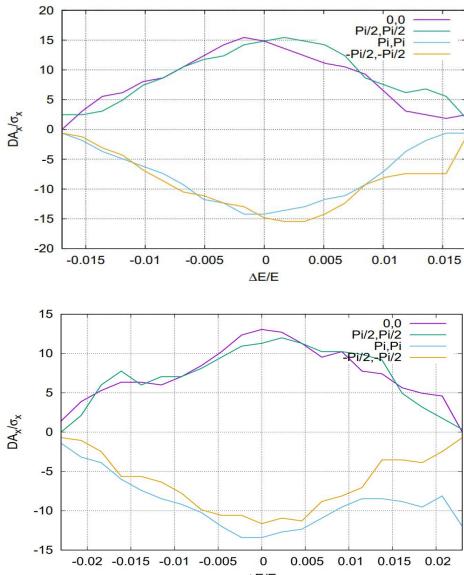
Volume II - Physics & Detector

The CEPC Study Group
October 2018

CEPC TDR Lattices of Half Ring for all Energies

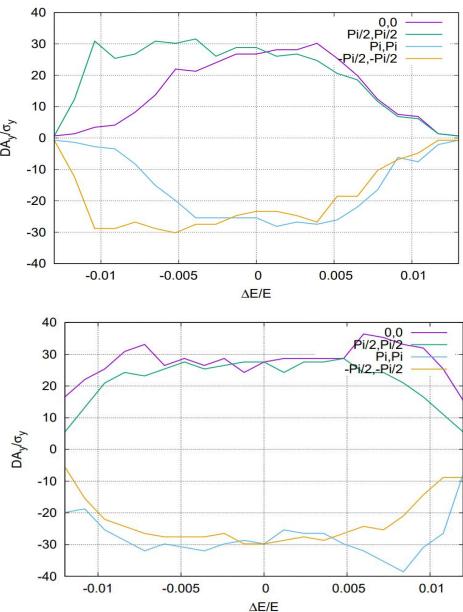
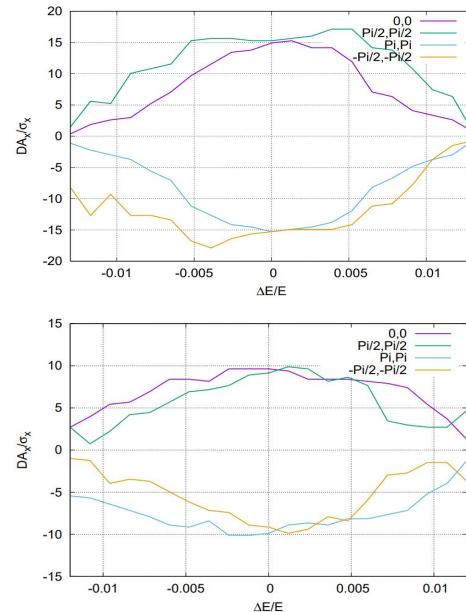
(tt-bar, Higgs, W and Z)

Effects included in tracking
Synchrotron motion
Radiation loss in all magnets
Tapering
Crab waist sextupole
Maxwellian fringes
Kinematic terms
Finite length of sextupole



Higgs

ttbar



Z

W

In addition to Higgs energy, tt-bar, W and Z modes' DA have been calculated and DA satisfy the requirements without errors, DA with errors for tt-bar W and Z will be included in the next step

CEPC 20GeV Linac Parameters

- Baseline scheme

- 20 GeV
 - Low magnetic field & large magnetic field range
 - C-band
 - Higher gradient → Shorter linac tunnel length
 - Small aperture & Strong wakefield
- 10 nm
 - High luminosity
- 100 Hz
 - Injection efficiency
 - High luminosity Z need faster injection process
 - 200 Hz
 - 100 Hz & two-bunch-per-pulse
 - 200 Hz & two-bunch-per-pulse (?)

Parameter	Symbol	Unit	Baseline
e ⁻ / e ⁺ beam energy	E_e/E_{e+}	GeV	20
Repetition rate	f_{rep}	Hz	100
e ⁻ / e ⁺ bunch population	N_{e-}/N_{e+}	$\times 10^{10}$	0.94(1.88)
		nC	1.5 (3)
Energy spread (e ⁻ / e ⁺)	σ_E		1.5×10^{-3}
Emittance (e ⁻ / e ⁺)	$\varepsilon_{x,y}$	nm	10

Parameter	Unit	S-band	C-band
Frequency	MHz	2860	5720
Length	m	3.1	1.8
Cavity mode		$2\pi/3$	$3\pi/4$
Aperture diameter	mm	20~24	11.8~16
Gradient	MV/m	21	45

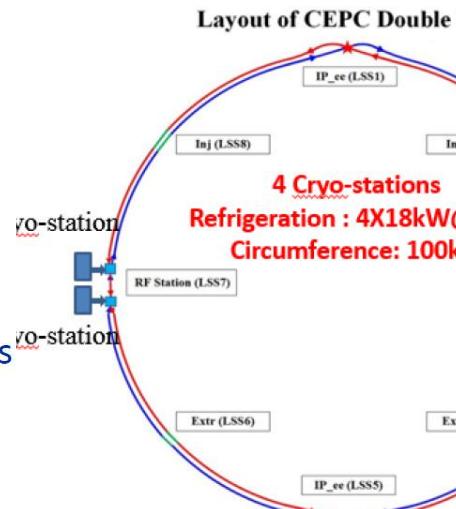
CEPC SRF Cryogenic Systems in TDR

Booster ring:

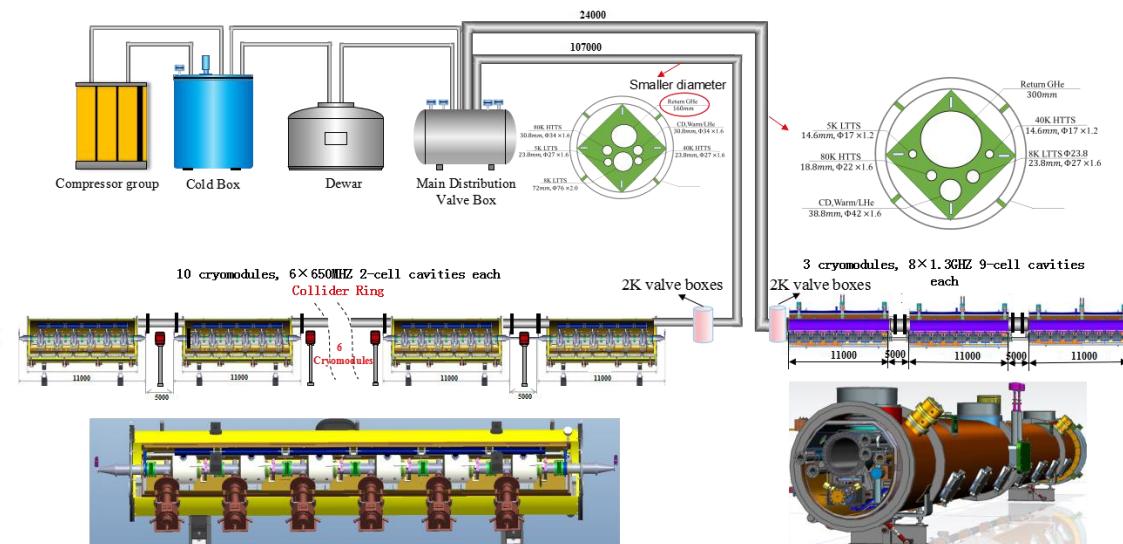
- 1.3 GHz 9-cell cavities, 96 cavities
- 12 cryomodules
- 3 cryomodules/each station
- Temperature: 2K/31mbar

Collider ring:

- 650MHz 2-cell cavities, 336 cavities
- 56 cryomodules
- 14 cryomodules/each station
- Temperature: 2K/31mbar



CEPC accelerator SRF cryogenic flow chart in TDR



For 30MW SR/beam Mode at Higgs energy, the cryogenic system need 32000liter Helium

For 50MW/beam SR Mode:

at Higgs energy, the cryogenic system needs 42000liter Helium; at ttbar energy
130000liter Helium needed

CEPC Accelerator System Key Hardware R&D Progresses in TDR

Technical Maturity

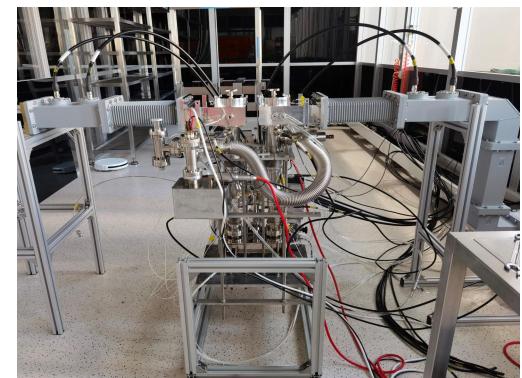
- Overall Technical Maturity:
 - 1 – Significant R&D required
 - 2 – Some R&D in a few key areas required**
 - 3 – Shovel ready
- Critical Technologies
 - SRF and needed R&D
 - High and high power efficiency RF power source and needed R&D
 - Magnets and needed R&D
 - ...See next list
- Technically limited timeline

2018 CDR, 2019-2022 TDR (R&D), 2023-2025 (EDR),

around 2026, Starting and +8 years construction

CEPC SRF Facilities and Components

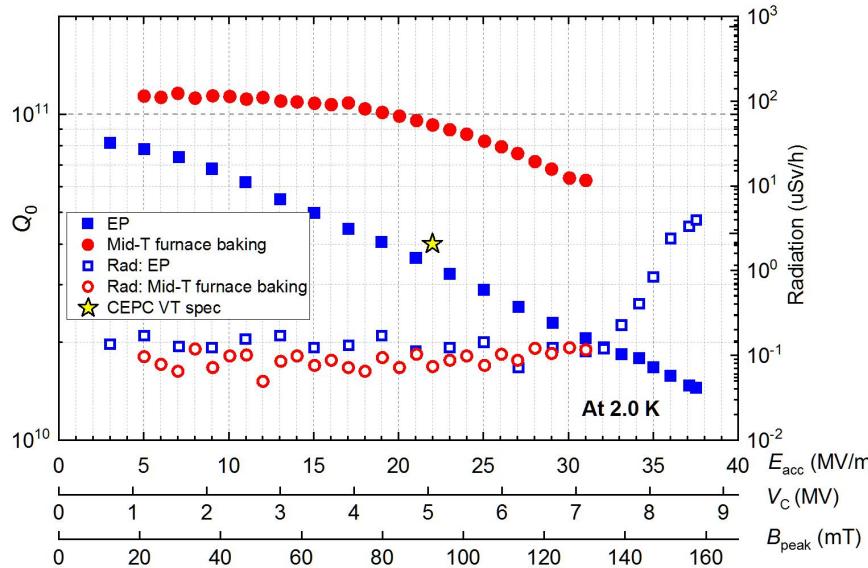
J.Y. Zhai, P. Sha



IHEP PAPS established in July 2021

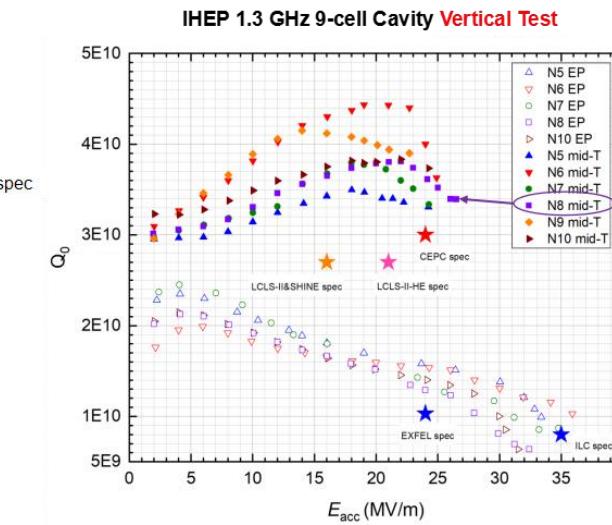
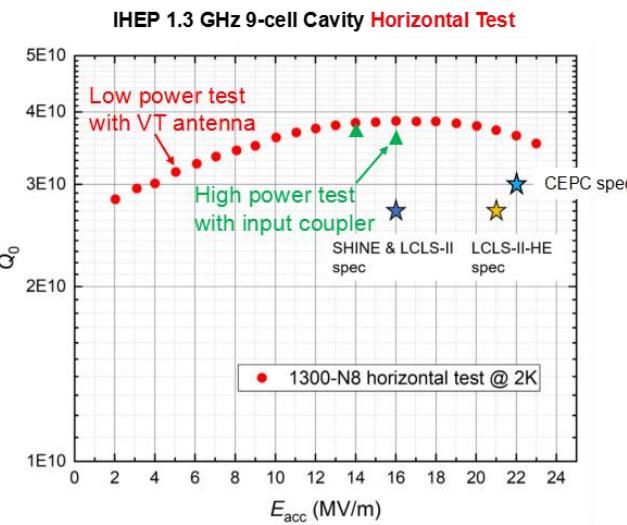
Horizontal test stand, 1.3GHz 9cell cavities, and couplers...

CEPC 650 MHz 1-cell Cavity



After Medium-temperature (mid-T) furnace baking, fantastic high Q of **6.4E10** was achieved at 30 MV/m.----World record **Q** for 650 MHz cavity!

1.3 GHz High Q Mid-T Cavity Horizontal Test

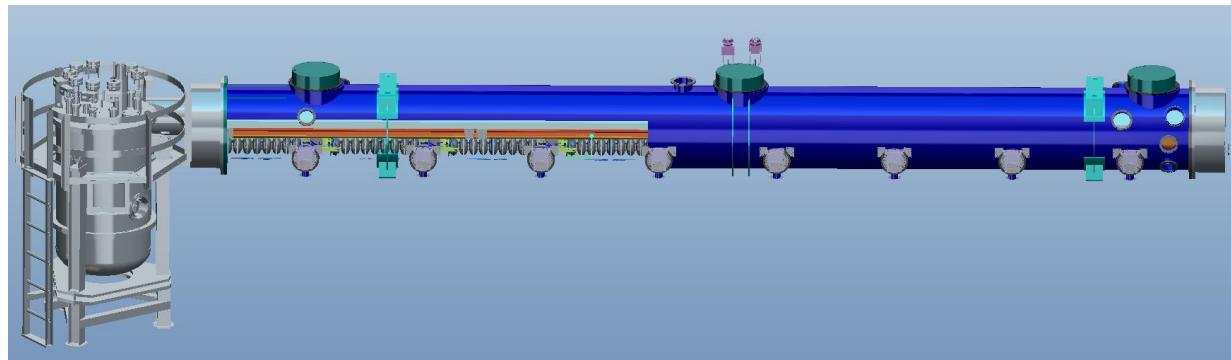


CEPC 650 MHz Test Cryomodule with Beam/ 1.3GHz High Q Cryomodule (8X9cell)



- Cavity string and module assembly in March to May 2021.
- Modul installation in beamline, 2 K cool down test and RT coupler conditioning in May to July. Horizontal and beam test soon.
- IR laser output to 116 W. Photo-cathode QE to 5 %. DC gun vacuum to 1.5E-10 Pa, voltage to 350 kV. Buncher cavity high power tested.

J.Y. Zhai



- 1.3 GHz 8x9-cell high Q cryomodule prototype
- Component fabrication in 2021 to mid 2022
- Assemble and horizontal test in 2022
- Ship to Dalian in 2023

CEPC 650MHz High Efficiency Klystrons

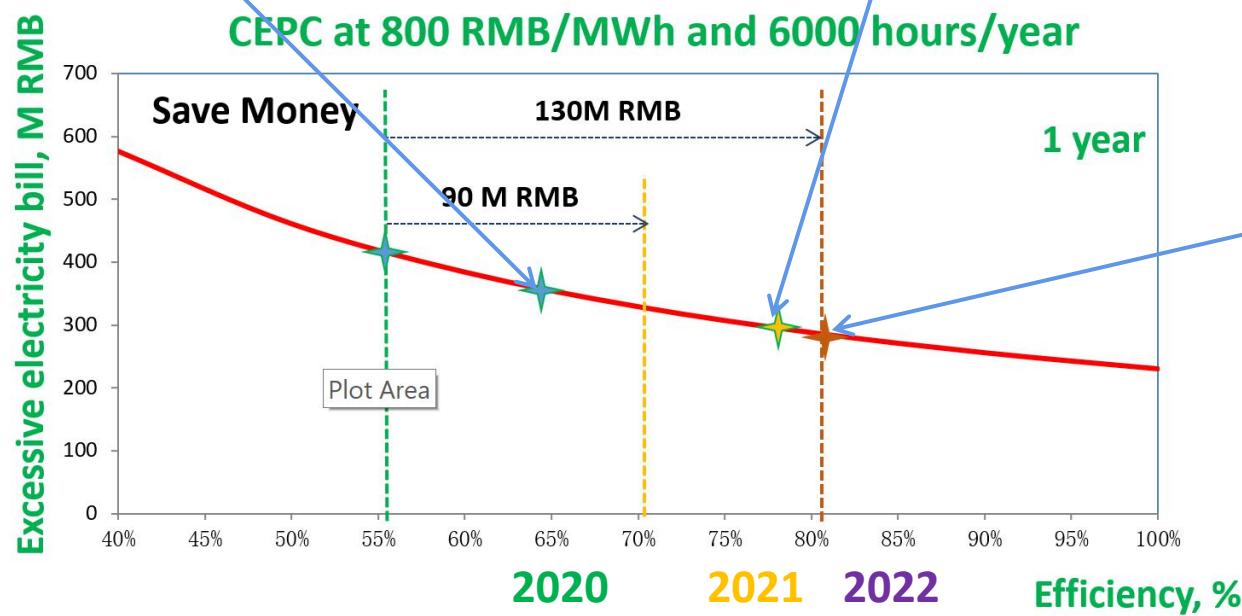
Z.S.Zhou



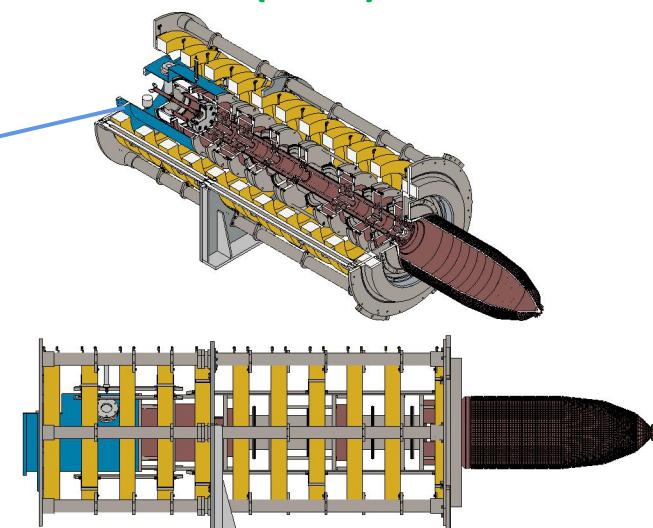
Klystron No. 1
Efficiency 65%
(2020)



Klystron No. 2
Efficiency 77%
(2021)



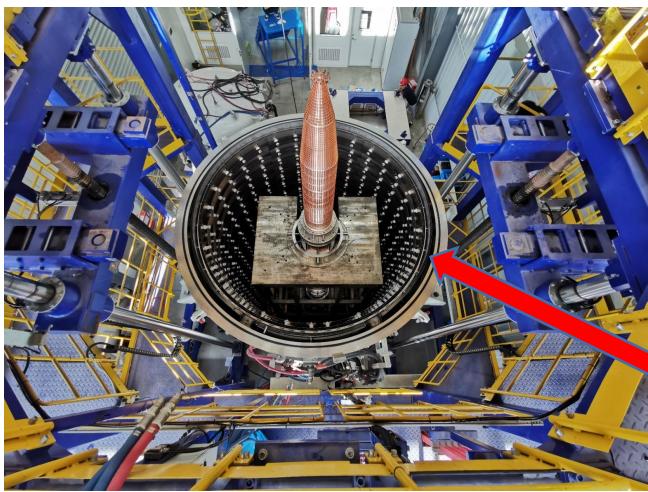
Klystron No. 3
Efficiency 80.5%
(2022)



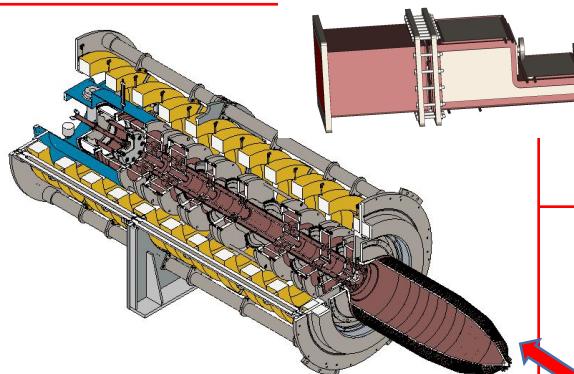
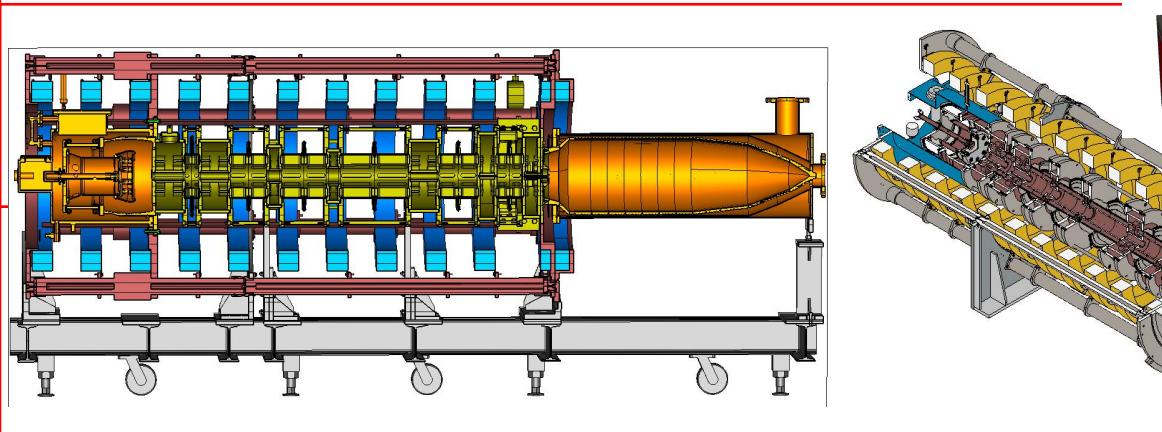
Efficiency impact on operation cost (Only considering operation efficiency of 650MHz klystrons)

CEPC 650MHz High Efficiency Klystrons (2nd and 3rd)

Z.S.Zhou



The 650MHz 800kW high voltage single beam klystron has been fabricated (77% efficiency) and installed at PAPS of IHEP in Dec. 2021, the test will start soon in 2022



Klystron No. 3
(MBK) Efficiency
80.5% (2022)

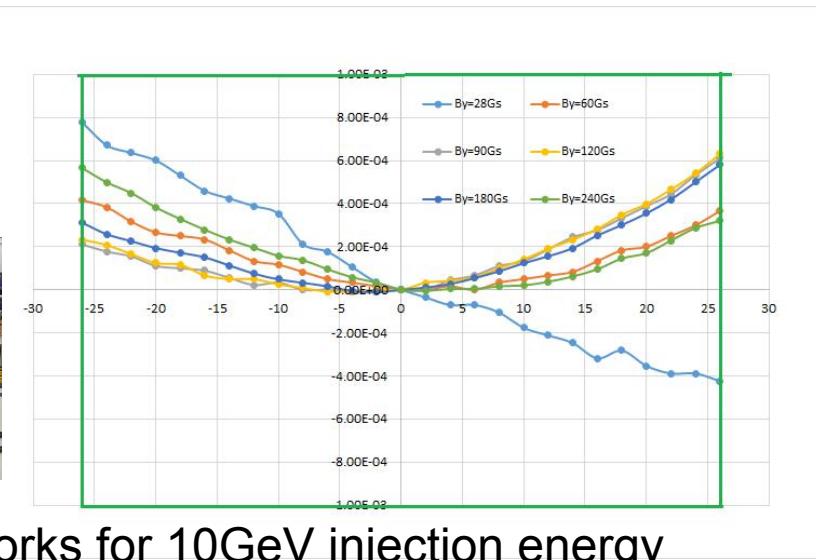
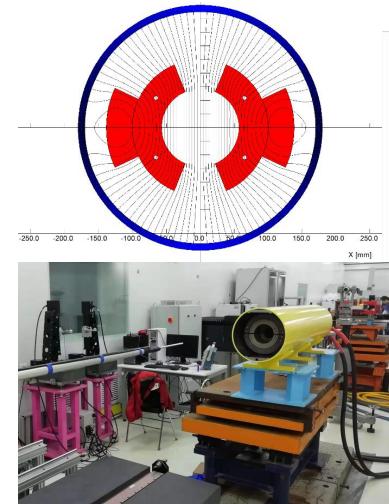
2021-12-16 J. Gao

FCPPL2021 workshop

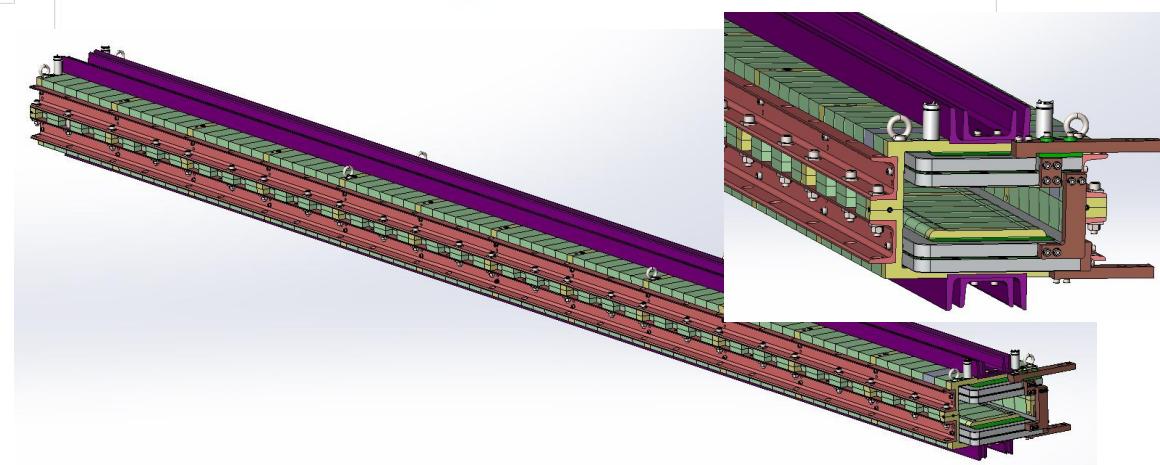
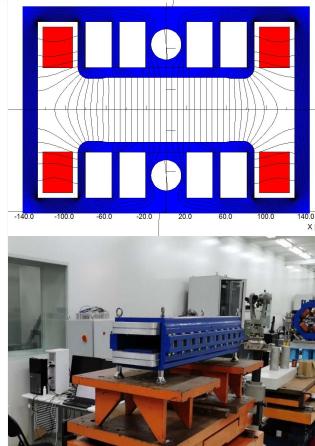
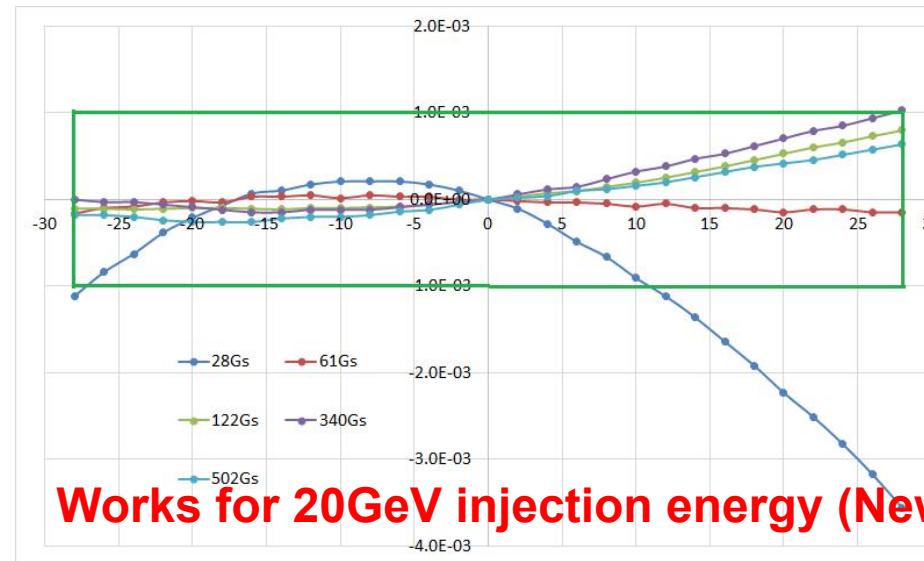
MBK Parameters	Value
Freq.	650 MHz
Output power	800 kW
Efficiency	80.5%
1dB band width	± 0.75 MHz
Cathode Voltage	54 kV
Cathode beam	2.51×8 A
Beam Number	8

CEPC Full Size Booster Dipole Magnets

W. Kang



Works for 10GeV injection energy

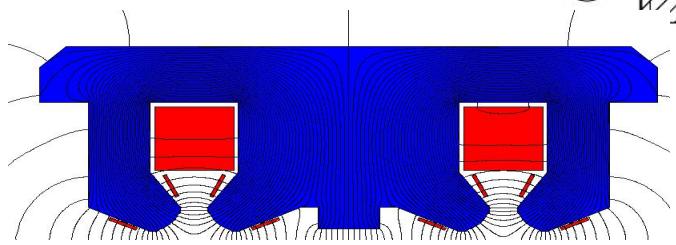
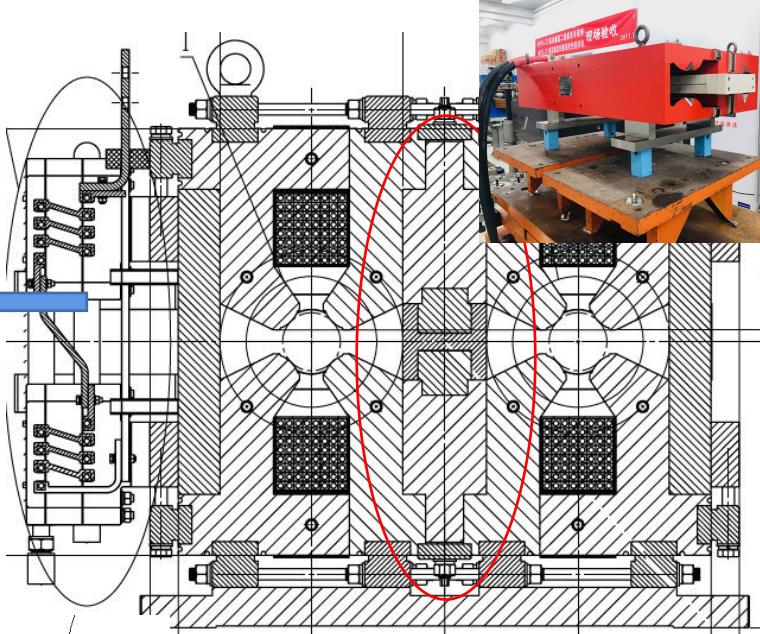
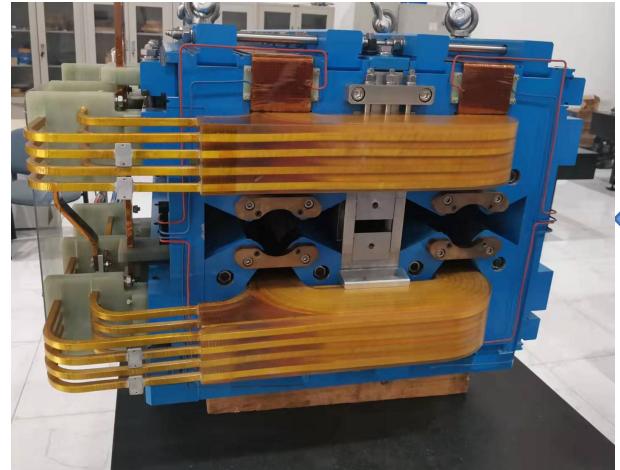


Two types of 4.7m long full size booster dipoles prototype fabrication in progress

CEPC Collider Ring Magnets

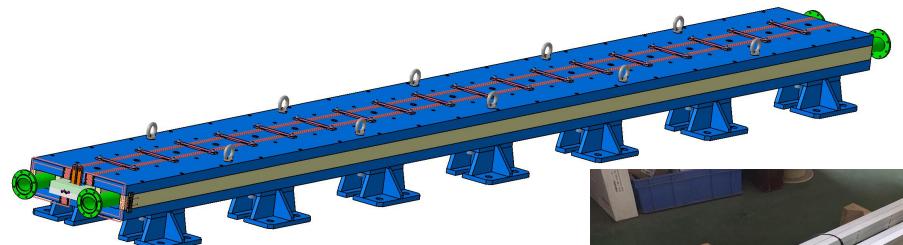
M. Yang

- Modification of the dual aperture quadrupole magnet

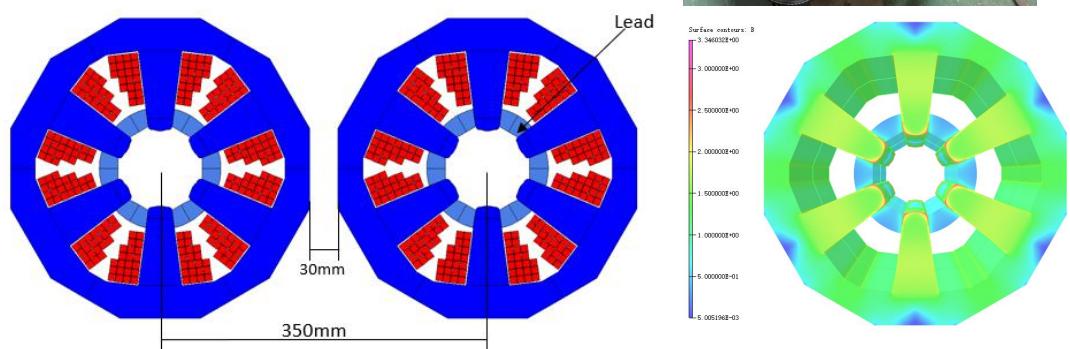
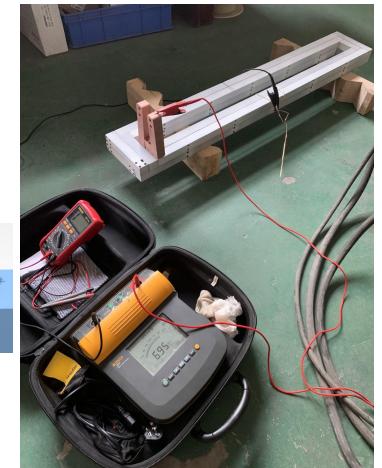
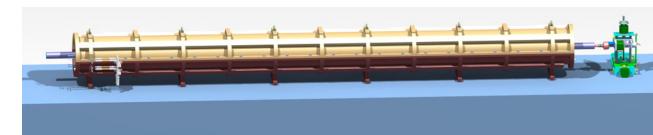


Dural aperture F/D quadrupole
design with trim coils

**Model experiment
verification:
Axis shift problem solved
in design**



Full size dural aperture dipole

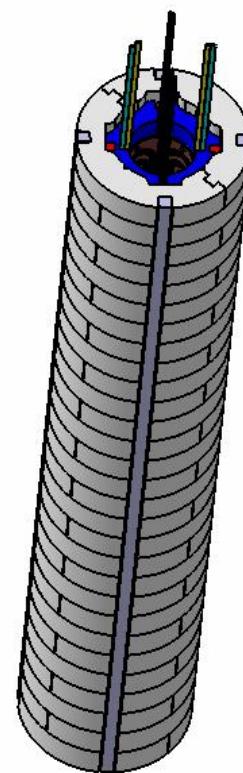


Sextupole design

CEPC QD0 SC Magnet R&D (0.5m short model)

Y.S. Zhu

Magnet name	0.5m QD0 model magnet
Field gradient (T/m)	136
Magnetic length (m)	0.5
Coil turns per pole	21
Excitation current (A)	2070
Coil layers	2
Conductor	Rutherford Cable, width 3 mm, mid thickness 0.93 mm, keystone angle 1.9 deg, Cu:Sc=1.3, 12 strands
Stored energy (KJ) (Single aperture)	2.6
Inductance (H)	0.001
Peak field in coil (T)	3.4
Coil inner diameter (mm)	40
Coil outer diameter (mm)	53
Yoke outer diameter (mm)	108
X direction Lorentz force/octant (kN)	24.6
Y direction Lorentz force/octant (kN)	-23.7
Net weight (kg)	25



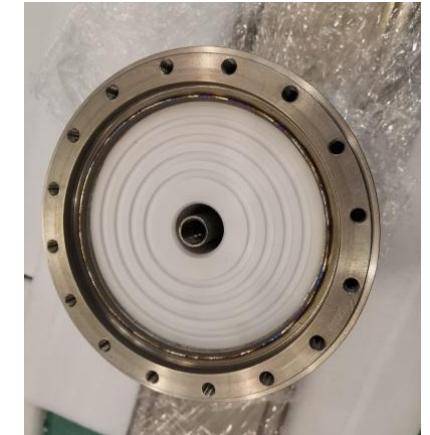
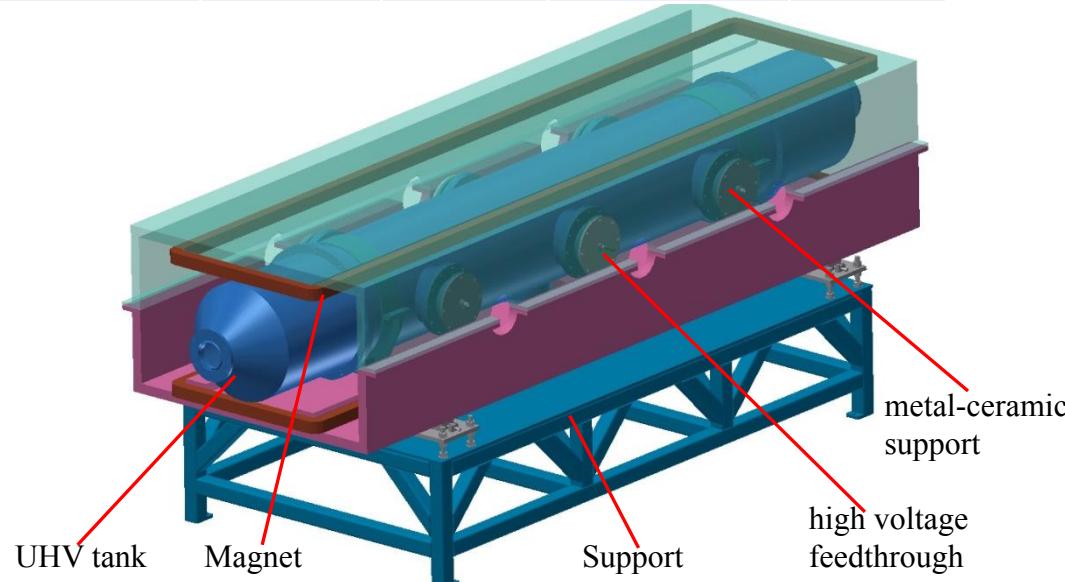
abrication of QD0 single aperture short model magnet (NbTi, 136T/m) is in progress, and a dual aperture SC quadrupole will be the next step

CEPC Electrostatic-Magnetic Deflector

B. Chen

- The Electrostatic-Magnetic Deflector is a device consisting of perpendicular electric and magnetic fields.
- One set of Electrostatic-Magnetic Deflectors including 8 units, total 32 units will be need for CEPC.

	Filed	Effective Length	Good field region	Stability
Electrostatic separator	2.0MV/m	4m	46mm x 11mm	5×10^{-4}
Dipole	66.7Gauss	4m	46mm x 11mm	5×10^{-4}

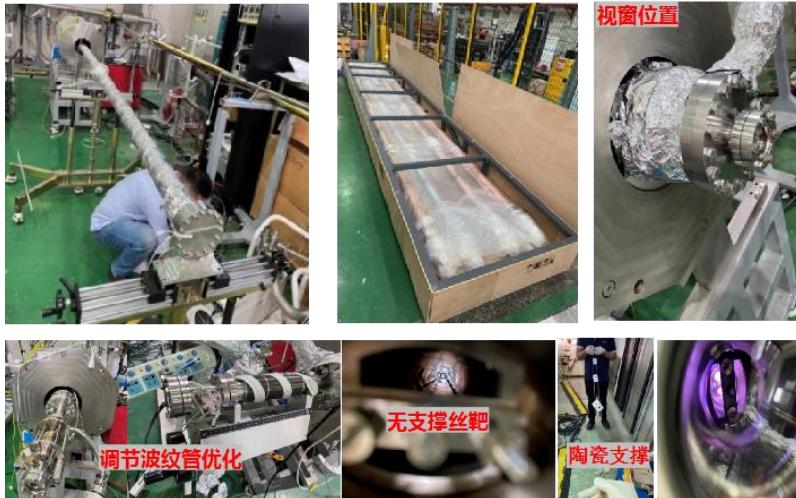
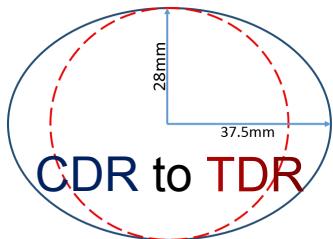


Electrostatic deflector will be installed into magnetic deflector soon in 2022

CEPC Vacuum System R&D

Y.S. Ma

New round pipe
of Copper (3mm)
with NEG coating
(200nm) for
collider ring
in TDR
 $SEY < 1.2$



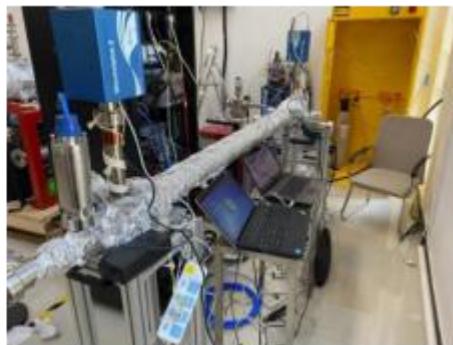
6 m vacuum pipe have been installed
on the NEG coating setup



All metal gate valve
different from VTA



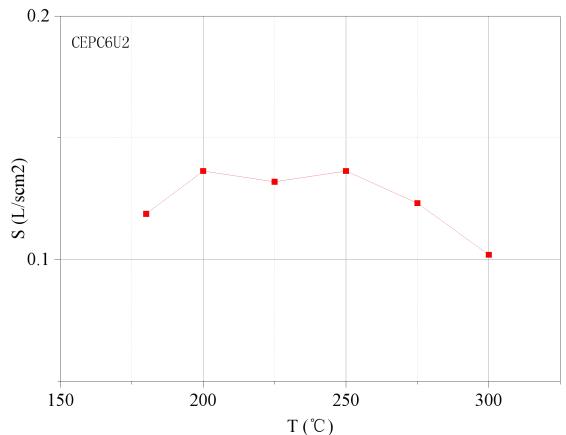
Vacuum pipes and RF shielding bellows



Facility of pumping speed test have been finished in Dongguan

1/19/2022 J. Gao

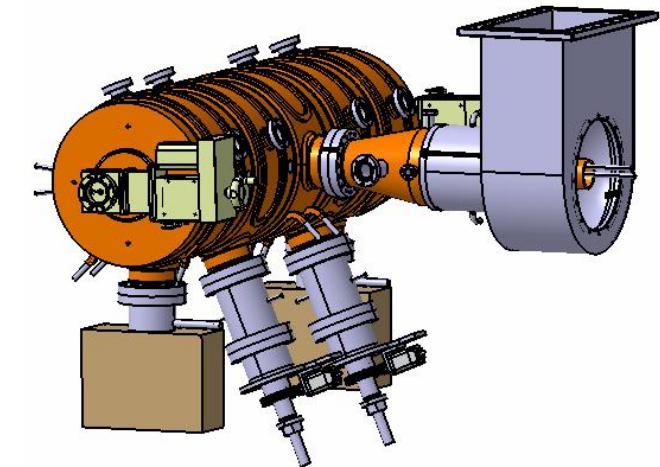
Snowmass Agora 2: Circular e+e- Colliders



Pumping speed test of 2 meters long
CEPC Cu pipe of NEG coating in IHEP

CEPC Injector Hardwares' R&D

J.R. Zhang



S-band high power test bench
and CEPC S band structure
 $E=33\text{ MV/m}$ reached

IHEP S band SLED :
Pulse length
 $4\mu\text{s} \rightarrow 0.8\mu\text{s}$

Positron flux concentrator
pulsed magnetic field of
6.2 T reached

IDamping ring 650MHz
RF cavity design



IHEP C band acc. structure V1:
 $E=40\text{MV/m}$, V2: $E=45\text{MV/m}$



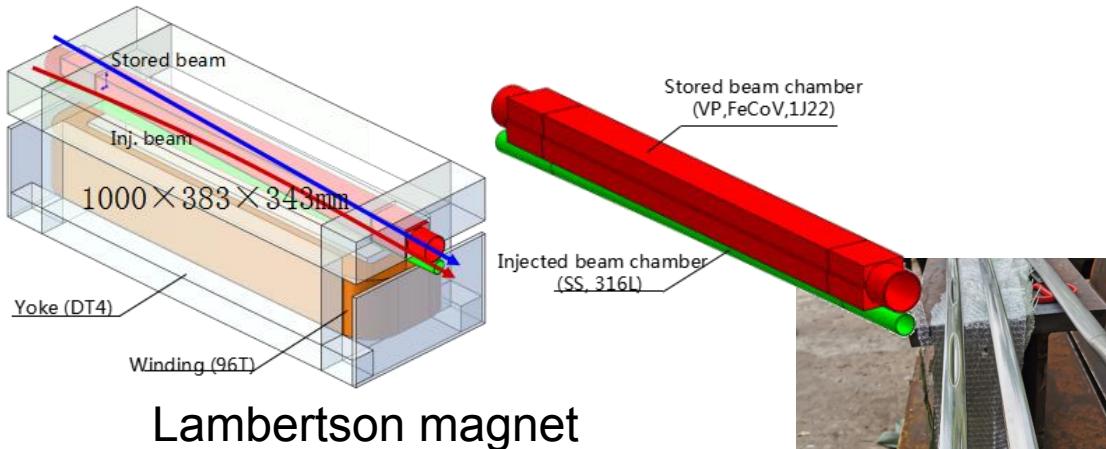
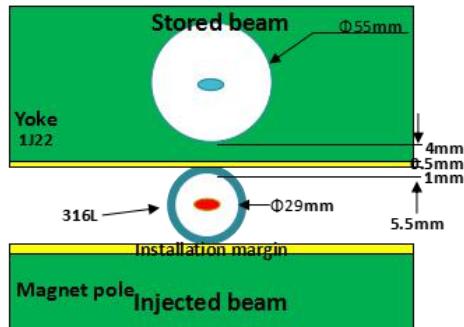
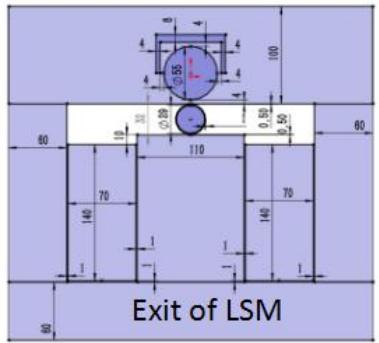
IHEP C band SLED
C band klystron design is starting



Shanghai SXFEL C band
linac, $E_{\text{max}}=41.7\text{ MV/m}$

CEPC Inj.&Ext. Hardwares' R&D

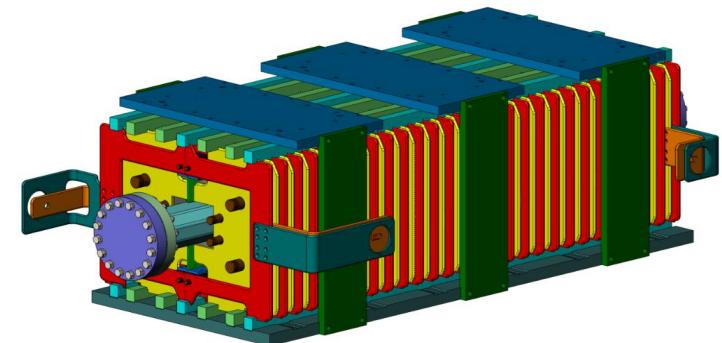
J.H. Chen



Lambertson magnet



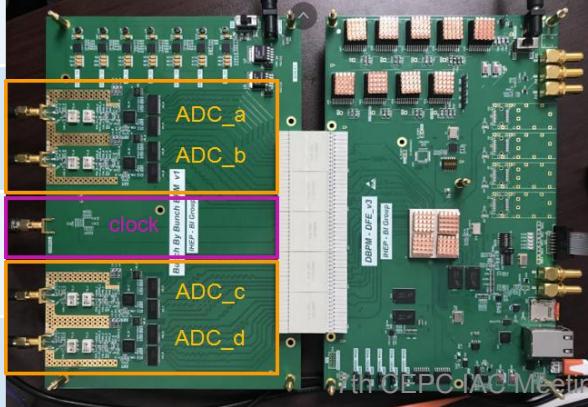
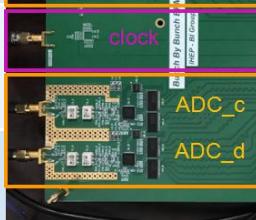
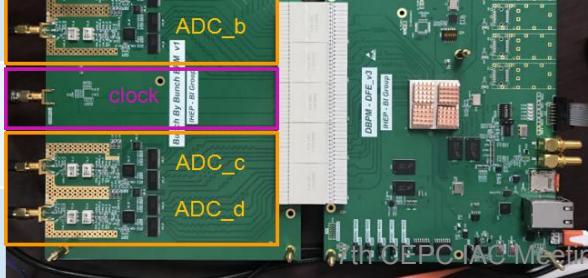
250ns-fast kicker
pulser



Delay-line dipole kicker

Status of CEPC Beam instrumentation R&D

Y.F. Sui

System	R&D Work supported by			Work to be done
	BEPCII	HEPS/HEPS TF	Funding	
BPM electronics	√	√	√	Radiation hardness Industrialization
Beam position monitor fabrication		√	√	detection;
Longitudinal feedback system	√	√		
Transverse feedback system	√	√		
Synchrotron radiation monitor				X-ray interferometer Gas jet scanning
BI at the interaction point			√	Special beam
Bunch current monitor				BBB electronics R&D based home-developed and company
Beam loss monitor 2021-11-1 J. Gao			√	beam loss detector R&D ; Industrialization

New Alignment Vision Instrument R&D

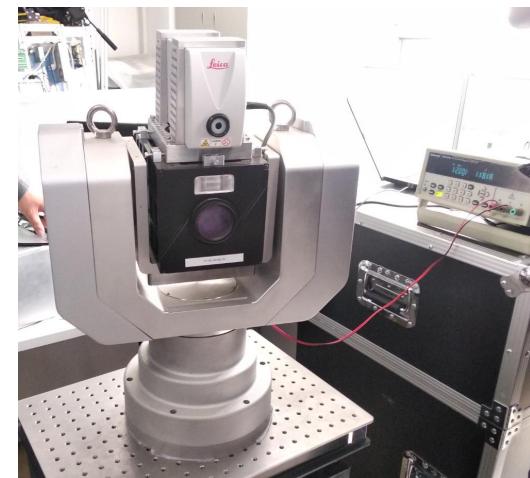
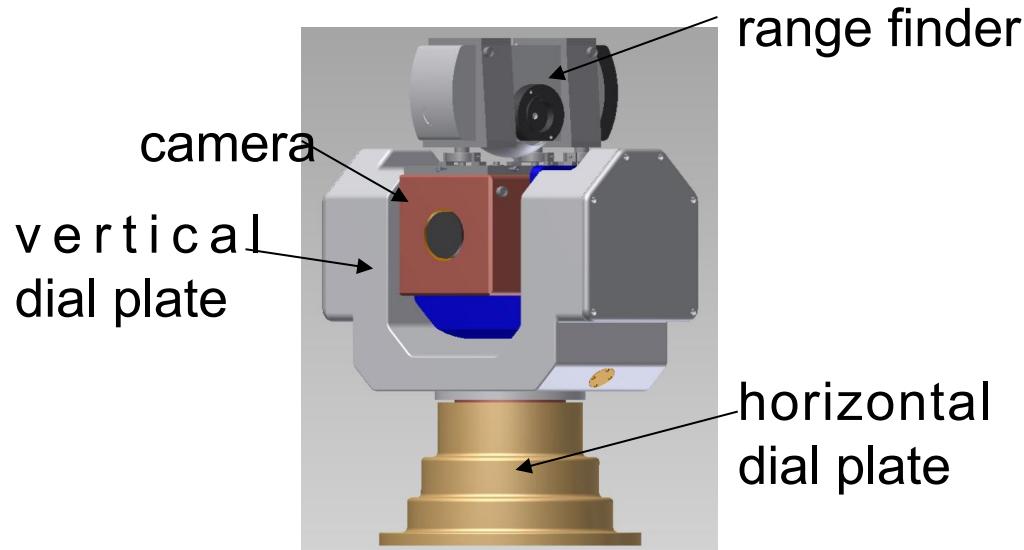
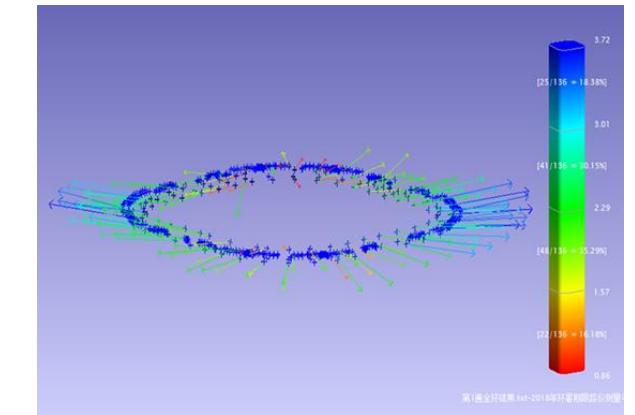
X.L. Wang

The new vision instrument can increase the efficiency by 4 times

A new kind measurement instrument with three fuctions:

1) photogrammetry, 2) distance, 3) angle measurement functions

➤ Objective: high precision, high efficiency



The completed vision instrument

Application test in RCS ring
of CSNS measurement



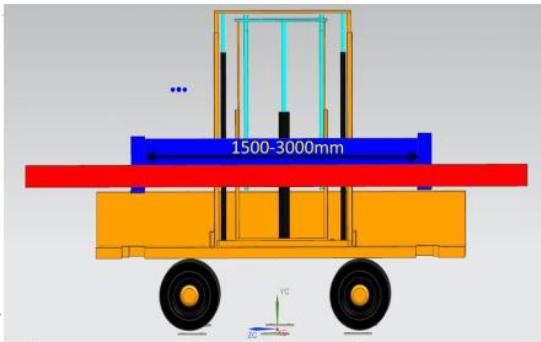
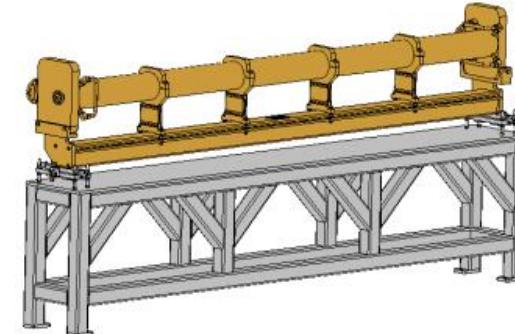
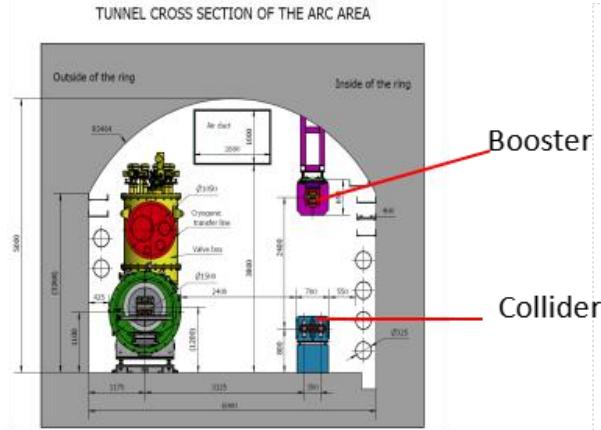
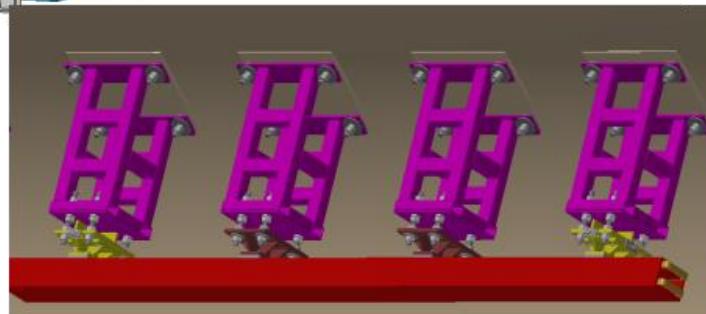
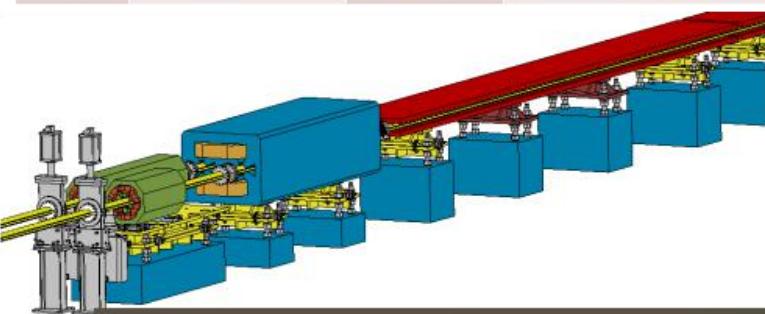
Five-face target R&D

CEPC Accelerator Mechanical Supports and Installation Tools

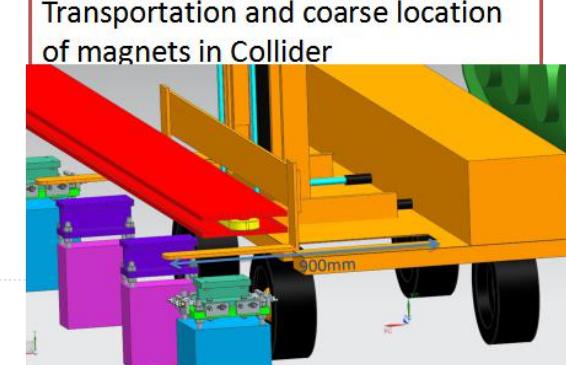
H.J. Wang

- Over 80% of the length is covered by magnets of about 138 types.

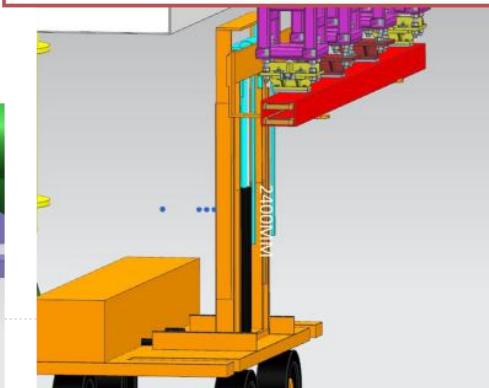
Adjustment Ranges of magnets			
X	$\geq \pm 20$ mm	$\Delta\theta_x$	$\geq \pm 10$ mrad
Y	$\geq \pm 30$ mm	$\Delta\theta_y$	$\geq \pm 10$ mrad
Z	$\geq \pm 20$ mm	$\Delta\theta_z$	$\geq \pm 10$ mrad



Flexible load support for
“long” devices and
“short” devices



Transportation and coarse location of magnets in Collider



2021-11-1 J. Gao

CEPC 18kW@4.5K Cryogenic Plant R&D

M. Li



Cryogenics Collaboration



2.5kW@4.5K Cryogenic Plant
successfully completed on April 7, 2021

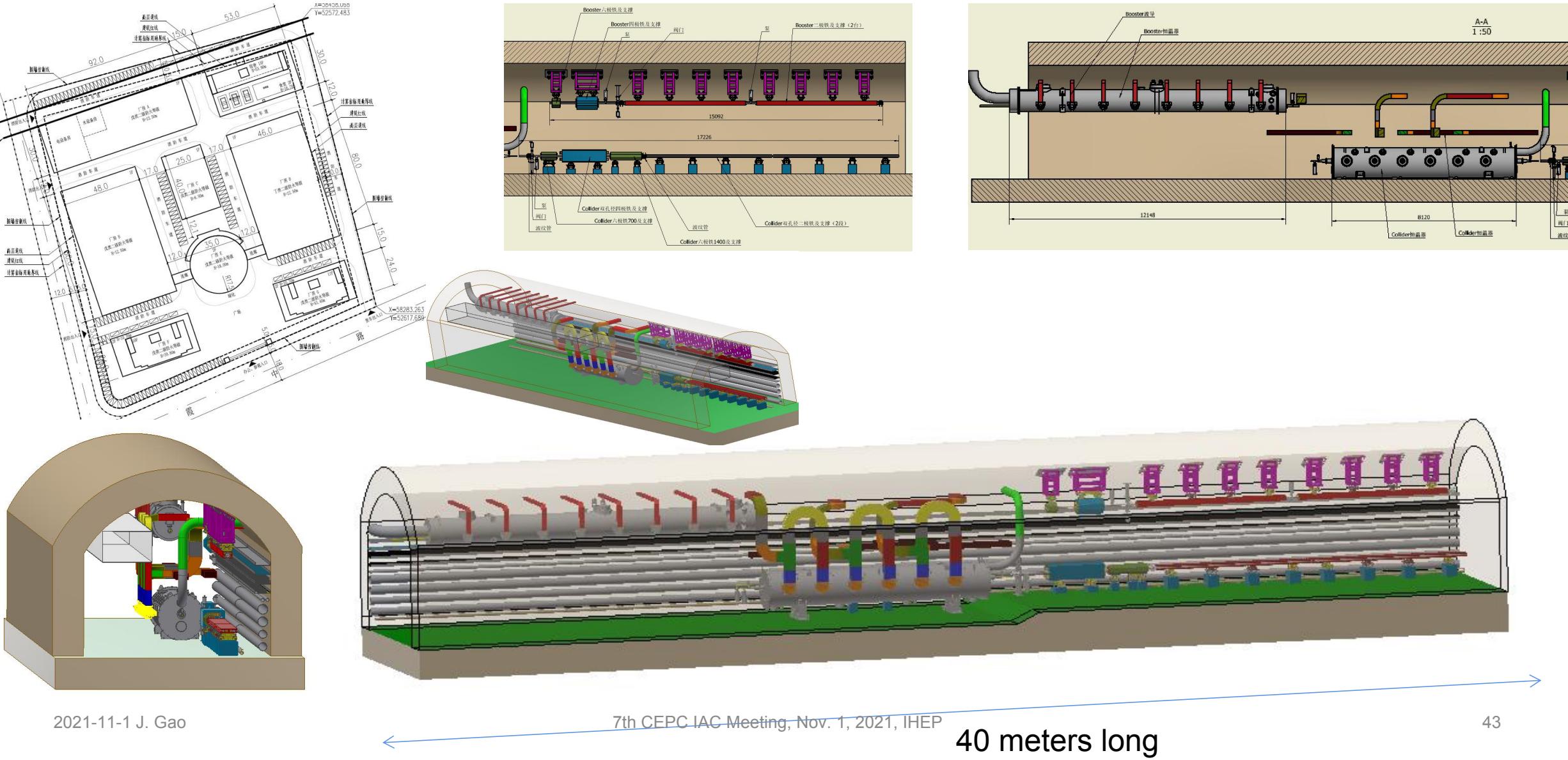


Milestone of Domestic Cryogenic activities



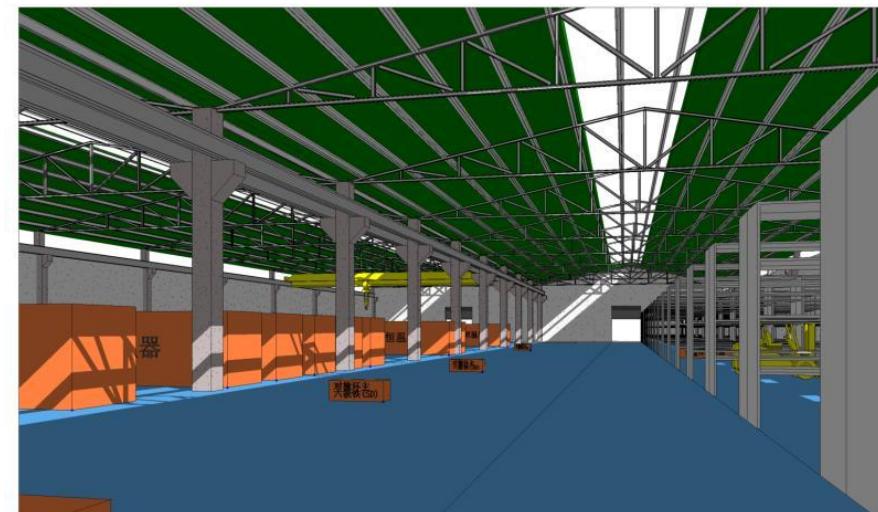
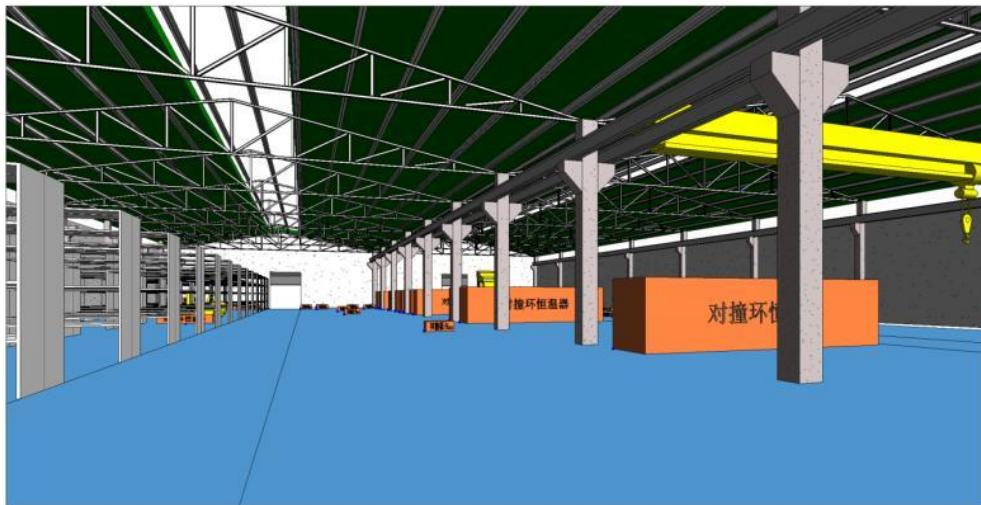
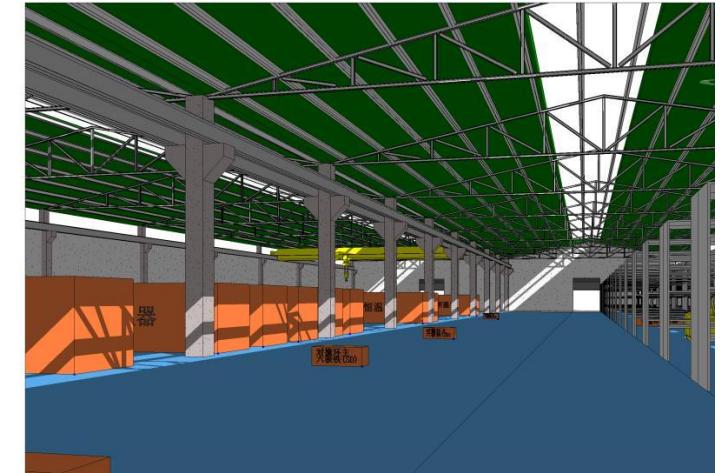
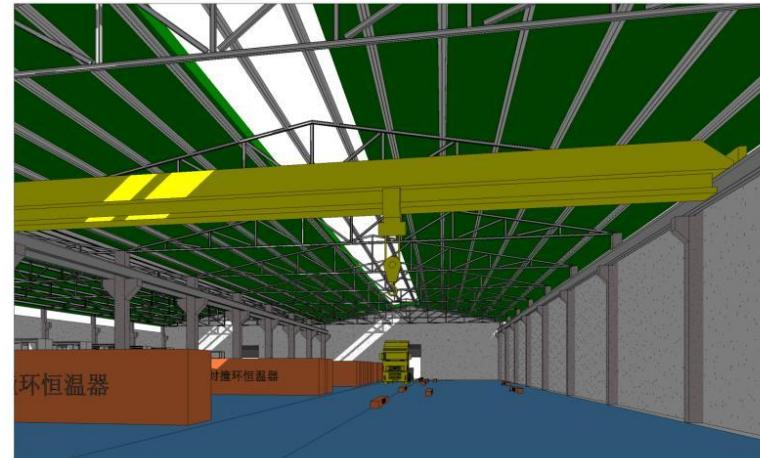
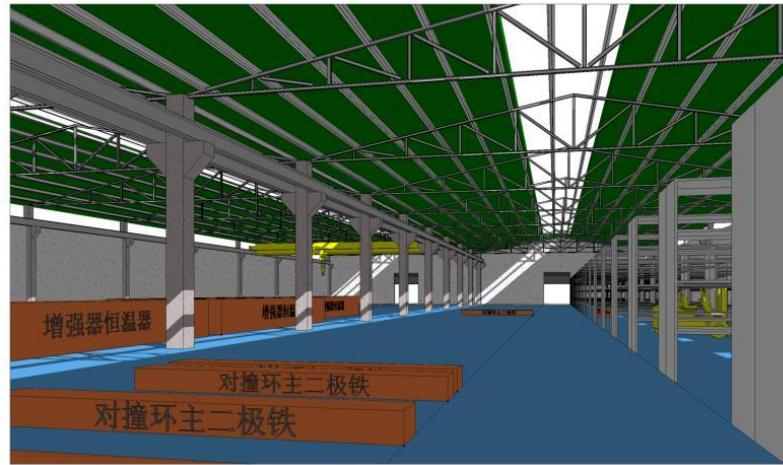
CEPC Tunnel Mockup Design

H.J. Wang

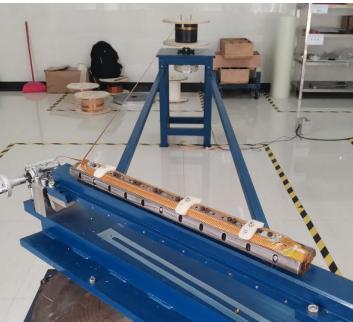


CEPC Component Stores for Installation Optimization

J.B. Wang



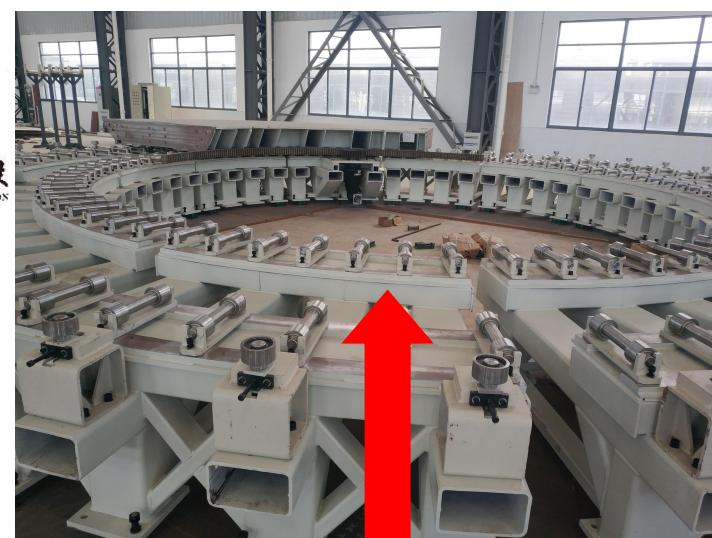
CEPC-CIPC Collaboration (part of CIPC members' logo)



CEPC 650MHz klystron at Kunshan Company

CERN LHC-HL CCT SC magnet

CEPC SC QD0 coil winding at KEYE Company



CEPC long magnet measurement coil

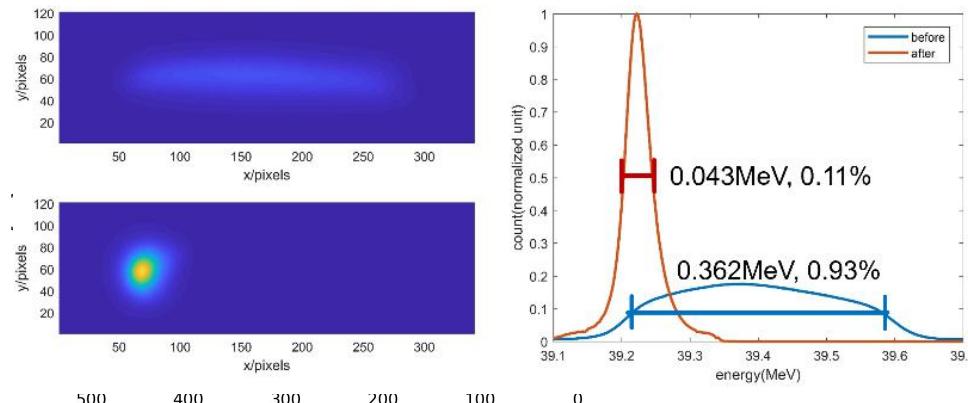
CEPC Detector SC coil winding tools at KEYE Company (Diameter ~7m)

CEPC Plasma Accelerator Injector (alternative)

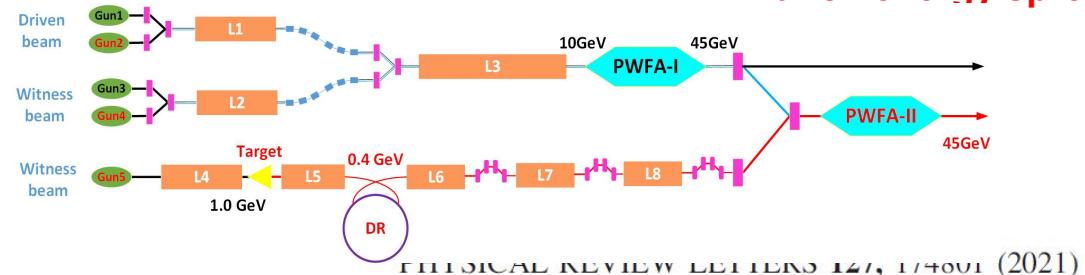
W. Lu, D.Z. Li

Booster Requirement

Energy (GeV)	45.5 (0.2%)
Bunch Charge (nC)	0.78
Bunch length(um)	<3000
Energy Spread(%)	0.2
$\epsilon_N(\mu\text{m rad})$	<800
Bunch Size(um)	<2000



Bunch energy spread 1% to 0.1%, exp at Tsinghua U.



Positron acceleration scheme made progress

High Efficiency Uniform Wakefield Acceleration of a Positron Beam Using Stable Asymmetric Mode in a Hollow Channel Plasma

Shiyu Zhou,¹ Jianfei Hua^{b,1}, Weiming An,² Warren B. Mori,³ Chan Joshi,³ Jie Gao,⁵ and Wei Lu^{1,4,*}

¹Department of Engineering Physics, Tsinghua University, Beijing 100084, China

²Beijing Normal University, Beijing 100875, China

³University of California Los Angeles, Los Angeles, California 90095, USA

⁴Beijing Academy of Quantum Information Sciences, Beijing 100193, China

⁵Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

HTR e- acceleration

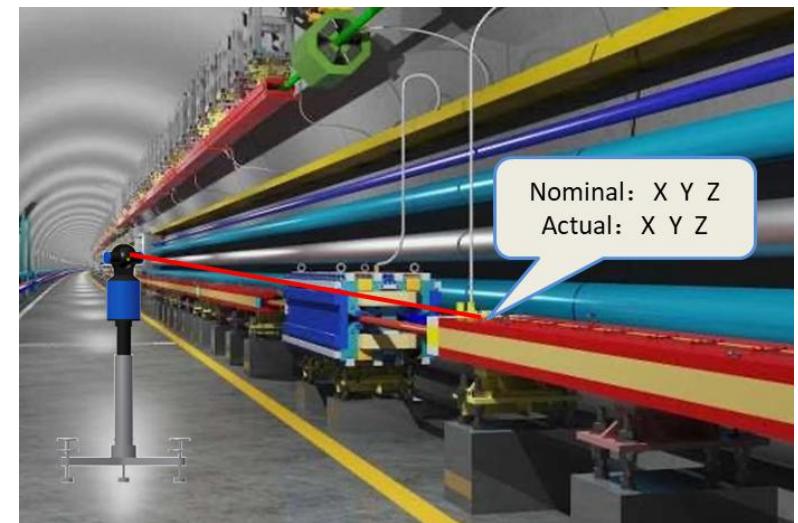
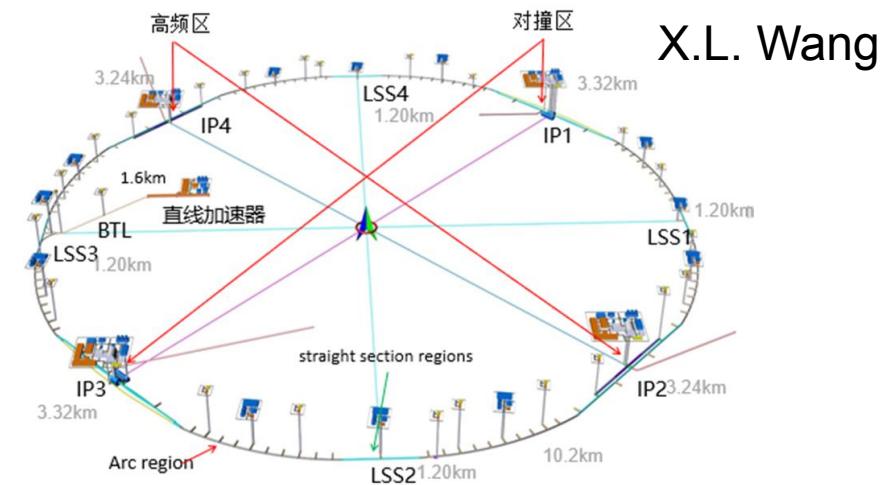
- Start-to-end simulation performed, CPI requirement to linac updated
- Without extra damping mechanism, the growth of hosing instability from statistical noise is acceptable when transformer ratio is 1-1.5
- There are other powerful damping mechanisms. HTR is still possible

e+ acceleration

- Asymmetry beam scheme is well accepted by PRL editor
- Experiments Plasma dechirper experiment got good results, energy spread from 1% to 0.1%
- Experiment on SXFEL is still ongoing. Dedicated TF for PWFA is crucial and under consideration

CEPC Accelerator Installation and Alignment

Component	Transversal/mm	Vertical/mm	Longitudinal/mm	Pitch /mrad	Yaw /mrad	Roll /mrad
Arc Dipole	0.1	0.1	0.1	0.1	0.1	0.1
Arc Quadrupole	0.1	0.1	0.1	0.1	0.1	0.1
Arc Sextupole	0.1	0.1	0.1	0.1	0.1	0.1
IR Quadrupole	0.05	0.05	0.05	0.05	0.05	0.05
IR SCQ	0.05	0.05	0.05	0.05	0.05	0.05
IR Sextupole	0.05	0.05	0.05	0.05	0.05	0.05

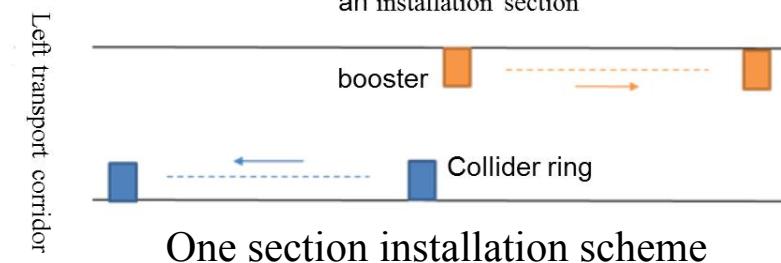
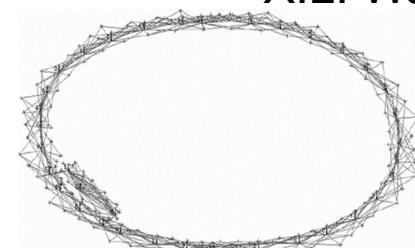
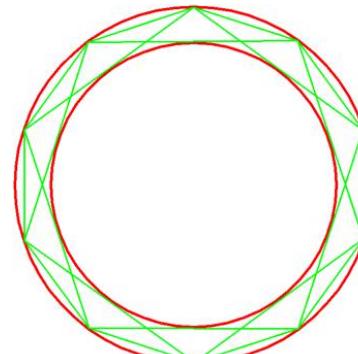
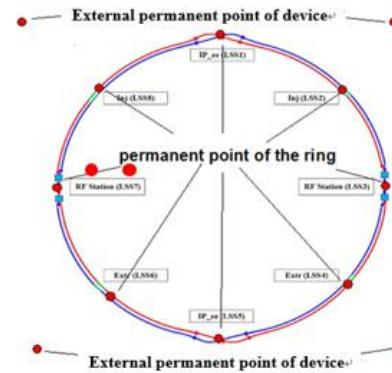
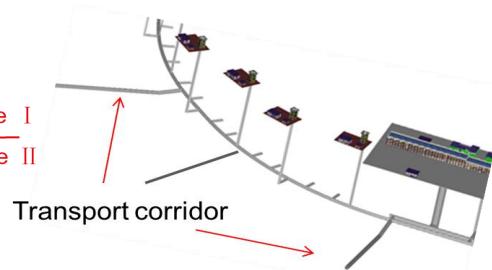
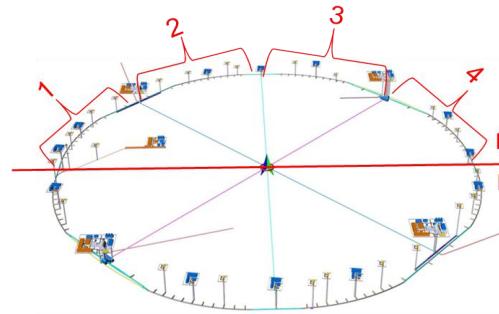


Workload of CEPC alignment

- Tunnel length 109.55km : 100.034km main ring + 6.64km IR booster tunnel + 1.21km Linac + 0.06km DR+ 1.07km BT + 2X0.268km BT
- Component quantities : 41563 ~ 52155
- Use laser tracker 18259 X2=36518 stations.

CEPC Installation and Alignment Strategies

X.L. Wang



middle transport corridor

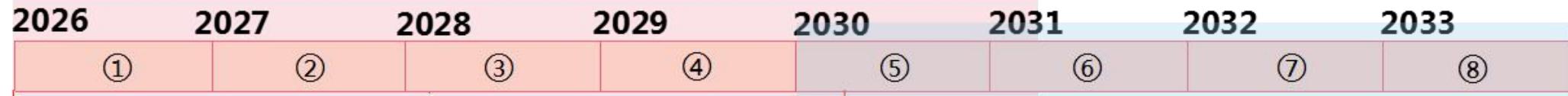
- CEPC civil construction will be divided into **two phases**, so the installation will follow it and include two phases
- In each phase the installation will be divided into **four sections** to be carried out in parallel
- 3 levels control network will be build to provide an unified location reference frame for CEPC alignment and control the error accumulation
- Component quantities : **41563**
- In the peak time, it will need **64** alignment groups and **56** installation groups
- Installation efficiency of each day has been estimated and the installation schedule has been made. According to the plan, the total installation time is **3 years and 8 months (44 months)**

Civil Construction and Machine Installations

Schedule analysis of CEPC construction

Overlap

Huadong Company



51 months (including project preparation) 2026.1~2030.3 TBM excavation

Total duration of CEPC project is 96 months

63 months 2026.1~2031.3 Drilling & Blasting excavation

2030.1~2030.12 12months

First-stage Control network construction and survey

1.CEPC production Including civil works and installation of physical equipment. It will begin in 2026 and end in 2033, The total duration of CEPC project is 96 months.

2030.10~2031.9 12months

Second-stage Control network construction and survey

2031.1~2032.6 18 months

Support installation and alignment

2031.3~2032.8 18 months

Dipole magnets installation

18 months

26032.9~2033. 10 months

Installation of other equipment

2.The total civil works period is 63 months.

3.The total installation period of physical equipment is 48 months

4. The Overlapping period of civil works and equipment installation is 15 months

Overall alignment and commissioning 6 months

2033.7~2033.12

Useful links

References:

- 1) CEPC CDR Vol. I, Accelerator, http://cepc.ihep.ac.cn/CEPC_CDR_Vol1_Accelerator.pdf
- 2) CEPC CDR Vol. II, Physics and Detector, http://cepc.ihep.ac.cn/CEPC_CDR_Vol2_Physics-Detector.pdf
- 3) F. An, et al., Precision Higgs physics at the CEPC, Chinese Physics C, Vol. 4, No. 4 (2019) 043002

CEPC Video (BIM design)

- 1) http://cepc.ihep.ac.cn/Qinhuang_Island.mp4
- 2) <http://cepc.ihep.ac.cn/Huzhou.mp4>
- 3) <http://cepc.ihep.ac.cn/Changsha.mp4>